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THE SEA

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PREFACE

UNDER the name of oceanography the science of the sea covers a broad field and deals with a great variety of interesting matters more or less intimately related. And like other sciences nowadays, it is growing on the technical contributions of specialists each engaged in cultivating intensively some small patch of the vast domain.

It is with the purpose of setting forth in nontechnical language the more salient features of our knowledge of the sea that this volume is written. No textbook on oceanography is here attempted, the author hoping that a less formal treatment may more clearly bring out both the importance and the inherent interest of the subject. With this in mind, too, various matters connected with the sea are here considered which ordinarily fall outside the scope of formal treatises.

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CHAPTER I

THE SEA OF ANCIENT TIMES

It must have been early in his life that Man stood on the shore of the sea and gazed questioningly out upon the waters. On a morning following some unusual storm he may have found a stick with strange carving, or a branch bearing unknown fruit, which the storm-driven waves had tossed ashore the night before. It had been a wild night, such as comes when the gods let loose the Furies. What lay beyond the rim of the impassable sea? Surely, the Evil Ones had their abode there, they who danced on the waters in mad abandon the night before, and whose grotesque shapes he had dimly discerned as he cowered affrighted in his shelter. But the strange fruit had a pleasant savor; perhaps, too, the Land of All Good Things lay out there beyond the horizon.

It is, obviously, difficult to reconstruct the ideas of mankind with regard to the sea prior to the appearance of written records. Gradually, some vague but coherent picture of earth and sea must have come into existence among the dwellers on the different shores of the sea. Some daring seamen venturing out beyond the customary routes would bring back strange tales of hitherto unknown regions; some ship driven out of its course by unusual winds or currents would, in the fortunate event of return, add something to the body of accepted belief. And so would arise some picture of the sea and its relation to the world.

Among different peoples different pictures of the world would arise; for obviously such a picture must have been very strongly colored by the physical environment in which a particular group found itself. And primitive man, it is to be remembered, lived his life within the restricted confines of limited areas, so that he had but little knowledge of regions differing greatly from his own. To the dweller on the bleak shores of a coast in high latitudes, the sea would be an entirely different thing than to the inhabitants of a palm-fringed island in the South Seas.

Not only would the physical environment color the picture of the world for a people in ancient times, but their religious views and more particularly their views with regard to the supernatural would likewise be of profound influence. Hence, when we speak of the notions regarding the sea in ancient times, it is with respect to the Mediterranean peoples that the term is used. For it so happens that the ancient peoples with whose history we are most familiar, and whose thought and knowledge have influenced us most, lived on or near the shores of the Mediterranean Sea. From the literature of these Mediterranean peoples, we can gain some notion of the sea as it appeared in ancient times.

In the poems of Homer there are various references to the sea, and we may take these as representing the knowledge current among the Greeks with regard to the sea about a thousand years before the beginning of the Christian era. Piecing together the various statements in these poems, the world as it appeared then consisted of a great flat disk made up by the countries bordering the Mediterranean Sea and neighboring lands. This disk constituted the habitable world, and around it flowed the all-embracing ocean, which was regarded as the origin and end of all things. The sea in Homer is the Mediterranean; the ocean is the great stream that surrounds the world.

The idea of a bounding ocean encompassing the habitable world appears to have been held among a number of the ancient peoples. With the Babylonians the ocean which surrounded the land was in turn encircled by the enclosing dawn. In the Hebrew Scriptures we read that the waters were gathered together in one place at the word of God and dry land appeared.

This picture of the world seems to have been the accepted one among the Greeks for a number of centuries. A modification, however, appears in the poems of Hesiod (about 750 B.C.). Mention is made of lands out in the ocean—the Isles of the Blessed, the Hesperides, Erythia—peopled by beings out of Greek mythology. The belief in the existence of these legendary isles became widespread in the ancient world and, as we shall see later, persisted for many centuries, being not without influence in the voyages of discovery of later times.

With the development of a more critical spirit in the following three or four centuries a less fanciful picture of the world emerges. The conception of the world as a sphere crops out now and again, and the first maps of the earth's surface are constructed. Another new idea gaining currency now is that of the division of the earth's surface into zones. The central zone is considered uninhabitable because of the heat of the sun; the two outermost zones are likewise considered uninhabitable because of their extreme cold; only the temperate zones, lying between the central and outer zones, are regarded as habitable.

The knowledge of the sea at this time may be regarded as summarized in the writings of the Greek historian Herodotus (about 450 B.C.). No longer is the habitable world a great island surrounded by an all-encompassing girdle of water. "I cannot refrain from laughing a little," says Herodotus, "at all those who undertake to describe the contours of the land without any facts to guide them; for ex-

ample, who represent the ocean as embracing the entire world in its course, who make it round as if drawn with a pair of compasses." He extends the land northward indefinitely, and speaks of the Atlantic Ocean, to which there was free communication through the Pillars of Hercules, as the Strait of Gibraltar was known to the ancients.

In Herodotus, too, we find the first mention of the tide. In the Mediterranean the tide is very small and its regularity is likely to be masked frequently by the disturbing effects of wind and weather. Hence, the Mediterranean people knew little of the tide. It is in describing an arm of the Red Sea that Herodotus mentions the fact that "every day the tide ebbs and flows therein."

While rejecting the idea of an encompassing ocean as unwarranted by any known facts, and while expressing doubts as to the existence of an ocean north of Europe and Asia, Herodotus takes for granted that Africa is surrounded by water, so that the Atlantic and Indian oceans form a single body of water. This he bases on the story which he relates of the circumnavigation of Africa by Phœnician mariners in the employ of the Egyptian king Necho. According to this story the expedition set out from the Red Sea, sailed down the east coast of Africa and after three years returned to Egypt through the Pillars of Hercules.

Much of the interest of Herodotus lies not only in the literary charm of his writings but also in the fact that he was an acute observer and that he traveled considerably, so that many of the details which he mentions are based on his own observations. Indeed, for his time, Herodotus must be considered an extensive traveler, notwithstanding the fact that his travels were limited almost without exception to countries of the Mediterranean basin. A century later, however, we come upon a Greek whose travels extended beyond the Mediterranean, into countries lying west of the Pillars of Hercules. This Greek, Pytheas by name, was a

native of Massilia, the Greek colony which flourished on the site now occupied by Marseilles. But before taking up his travels, it will be of advantage to mention briefly two other Greeks whose lives span the century between Herodotus and Pytheas. Plato and Aristotle must be mentioned in the story of the sea even though their names are generally associated with other domains of knowledge.

Plato was born about fifty years after Herodotus; and while he occupied himself almost exclusively with philosophy, it is in his writings that we come upon the story of Atlantis, an island in the sea beyond the Pillars of Hercules. This island, according to the story which Plato relates as coming from an old Egyptian priest, was the seat of "kings of amazing power," but disappeared beneath the sea "with great earthquakes and inundations, in a single day and one fatal night." This is represented as having happened about nine thousand years previously, but "since that time the sea in these quarters has become unnavigable; vessels cannot pass there because of the sands which extend over the site of the buried isle."

The story of Atlantis as related by Plato has made a very strong appeal for many centuries and later it will be necessary to consider it in greater detail, in connection with the question of legendary isles. Here it is important to notice it for the fact that inhabited lands out in the ocean are taken for granted, and for the further fact of the mention of areas in the open sea that are unnavigable. This latter idea acted as a strong deterrent throughout a considerable period of time against undertaking voyages of exploration into the open ocean.

Aristotle came about forty-five years after Plato, of whom he was a pupil. In Aristotle's writings we find that he regarded the earth as a sphere, one of the reasons cited in support of this being the circular appearance of the earth's shadow during eclipses. The habitable world he

confined to the temperate zones, adding that in the souther hemisphere there must certainly be a temperate zone co responding to that in the northern hemisphere. With re gard to the sea beyond the Pillars of Hercules, howeve his notions are vague and erroneous, for he regards it a muddy and shallow, this view apparently being the ger erally accepted one among the Greeks at that time.

With Pytheas the geographic horizon widens and th Atlantic Ocean comes within the sphere of the known worlc Through Pytheas the ancients became acquainted wit western Europe and more particularly with the Britis Islands. The extent of his travels is not known accuratel for unfortunately his writings are all lost, and our know edge of him and his journeys is based on casual mentio by later writers. In fact, even the period in which he live is not known exactly. Apparently he was in his prim about 325 B.C., and was the author of a book on the sea i which he gave an account of his travels. There is no que tion, however, that he was an able astronomer, for at tha early date he determined the latitude of Massilia with su prising accuracy.

According to the information that has come down to u from later writers, Pytheas had given an account of a voy age he had made to Britain, a large part of which countr he explored. From him the ancient Mediterranean worl got definite information of this large island in the Atlanti He gave account further of an island which he calle Thule, lying six days' sail to the north of Britain. In th region of Thule, Pytheas related, the sea became of a thic and sluggish nature, like neither land nor sea, which mac navigation impossible.

On the shores of the British Islands the rise and fall c the tide is much greater than in the Mediterranean, an to Pytheas it must have been an impressive phenomeno The very nearly constant relation between the time of tic

and the moon's meridian passage, and also the regular variation in the height of tide with the waxing and waning of the moon point so clearly to some intimate connection between moon and tide that a keen observer like Pytheas could scarcely fail to note it. And it is to Pytheas that the earliest recorded mention of this intimate relation between moon and tide is credited.

Some three hundred years before the beginning of the Christian era, therefore, the ancient world was becoming familiar with the northeastern coast of the Atlantic Ocean and with some of its outlying islands. But the path opened up by Pytheas remained unfollowed, so far as known, for more than two centuries, and during that time there was no considerable addition to the knowledge of the sea. During this time, however, geographic knowledge became systematized and coördinated, and in this work Eratosthenes may be taken as the leading figure.

Eratosthenes (276-196 B.C.) was one of the most learned men of antiquity and the author of a number of books on various subjects. As librarian of Alexandria he occupied a post of distinction, for the library of Alexandria was the most important and most celebrated in the ancient world. Of his writings only fragments remain; but these, together with the references of later writers, make it evident that his aim was to bring together the existing geographic knowledge and to construct a map of the world in consonance with this knowledge.

An educated Greek of that time took the sphericity of the earth for granted; but Eratosthenes went further and arrived at the surprisingly correct estimate of about 25,000 miles for the circumference of the earth. What makes this of special significance is not the closeness of his approximation to the true circumference, for the means at hand for making the necessary measurements were so crude that he might very easily have arrived at a different result: the

significant feature is that he used strictly scientific principles.

On his map, which was confined to the habitable world as known at that time, Eratosthenes drew a system of lines parallel to the equator and another system perpendicular to these—introducing, in fact, parallels of latitude and meridians of longitude. While this map coördinated the existing geographic knowledge, it was erroneous in numerous details, as was to be expected from the imperfect data which he had at his command. For it is to be borne in mind that the means at that time for determining latitude, and more especially longitude, were very imperfect.

To Eratosthenes, too, must be credited the first recorded mention of the theoretical possibility of circumnavigating the globe. "If it were not that the vast extent of the Atlantic Sea rendered it impossible," he said, "one might even sail from the coast of Spain to that of India along the same parallel."

Eratosthenes regarded Africa as surrounded by the ocean, which idea we have already found in Herodotus two hundred years before. But that this was still a debatable question is evident from the fact that in the following century, Hipparchus, one of the very greatest of the ancient astronomers, challenged the correctness of this idea. He based his rejection of this idea on the ground that certain Babylonian observations on the tide were incompatible with it, and he could therefore not admit that the Atlantic and Indian oceans were continuous.

The wars of the Romans in western Europe made accessible to the ancient world at this time a much better knowledge of the geography of that region; but little new knowledge with regard to the sea appears. The Greek historian Polybius, who was a contemporary of Hipparchus, made use of this new geographic knowledge in his writings; but he, too, is skeptical with regard to the continuity of

the Atlantic and Indian oceans, giving it as his opinion that it could not be stated with certainty whether or not Africa is surrounded by water.

It is a curious fact that although our knowledge of the travels of Pytheas comes from a passage in Polybius, he himself rejects Pytheas' account of Britain and Thule, treating it as fiction. According to Polybius the knowledge of northern Europe and the British Islands was of a very vague nature. With regard to the equatorial regions, however, he adopts the view suggested by some previous geographer that in the immediate neighborhood of the equator the heat was much less intense than in the torrid zones on each side of it, so that it was habitable, and in fact was inhabited.

Some fifty years later, or about a hundred years before the beginning of the Christian era, the Greek philosopher Posidonius wrote a book which was entitled *On the Ocean.* This work, like so many other Greek works, has not come down to us; but from quotations and references to it by succeeding writers, it must have been a veritable mine of information. In this work Posidonius attempts a new determination of the circumference of the earth. His method was somewhat different from that of Eratosthenes, but like it strictly sound in theory. But the measurements he made use of were so crude that he arrived at a much smaller figure, namely, about 18,000 miles. This much reduced circumference of the earth came to be the generally accepted one by later Greek writers.

With regard to the unity of the Atlantic and Indian oceans, Posidonius disagreed with his more immediate predecessor Polybius and followed the view of Eratosthenes. In his opinion, ~~the~~ circumnavigation of Africa was quite possible. He does follow Polybius, however, in assuming that immediately under the equator the temperature was milder than in the torrid zones to the north and south of it.

Posidonius appears to have arrived at clear ideas with respect to the tide. He had spent some time on the Atlantic coast of Spain where the rise and fall of the tide averages about ten feet—much greater therefore than in the Mediterranean. From his own observations, and from the information he received from the natives, he arrived at a correct idea of the variation of the tide with the moon's changing phases. To Posidonius, too, is credited the first recorded reference to a deep-sea sounding. This occurs in a statement in which he is quoted as having said that "the greatest depth of any sea that had been measured was that of the Sardinian Sea which was not less than 1,000 fathoms."

Apparently Posidonius was impressed with the possibility of changes in the earth's surface as a result of earthquakes or volcanic action. He himself recorded the appearance of a new islet, thrown up by volcanic agency, among a group of islands near Sicily. And in this connection he is represented as having suggested that Plato's story of Atlantis, instead of being fiction, may hark back to an island the size of a continent which really disappeared into the depths of the ocean.

When we come to the beginning of the Christian era, we find the Mediterranean still the center of the ancient world. Now, however, Rome is the leading state, its power extending all over the Mediterranean. The geographic knowledge of the ancient world at this time is preserved for us in the *Geography* of Strabo, a Greek writer, whose life of some eighty-odd years extended into the third decade of the first century of the present era. This *Geography* is regarded as the most important geographical work that has come down to us from antiquity.

Strabo's aim in his *Geography* was to bring together all the geographic knowledge of the time. He had traveled widely, and had spent a considerable time in Alexandria,

in the famous library of which he had access to the works of the earlier Greek writers. Indeed, this latter fact constitutes no small part of the importance of Strabo, for it is chiefly through his references and citations that we derive our knowledge of the earlier Greek geographers. As we have already had occasion to observe, the works of many of the early Greek writers have been lost. It is to Strabo, for example, that we are indebted for nearly all we know of the Greek maps made prior to his time, for none of these maps has been preserved.

Strabo was primarily an historian and not a mathematician or an astronomer. In common with the great majority of Greeks of his day, he regarded Homer as the source of all wisdom and knowledge, whose statements might indeed require explanation or interpretation, but were not to be regarded in any sense erroneous. The attitude of the Greek world toward Homer at the time of Strabo is well summarized in the following words by a modern scholar: "The blind reverence paid by most Greeks of his day to the works of the great poet was little short of that with which many other nations are accustomed to regard their sacred books—as an authority paramount to all others, which it was rank heresy to dispute or question."[1]

This explains why Strabo discusses quite seriously the voyages and exploits of the legendary Greek heroes, and yet is skeptical with regard to information found in Herodotus and Eratosthenes. He censures Eratosthenes severely for having given credence to the accounts of Pytheas, whom he considers altogether unworthy of credence, and he, therefore, discards altogether the existence of Thule.

The greater part of his *Geography* Strabo devotes to a detailed discription of the various countries. That falls outside our present concern. It is with regard to the

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[1] E. H. Bunbury, *A History of Ancient Geography*, Vol. II, p. 214.

general geographic ideas current at that time that Strabo interests us in a story of the sea—the ideas in regard to the shape and size of the earth, the relation of land to sea, the possibility of the existence of other inhabited lands. With regard to these, Strabo takes for granted that the earth is spherical and adopts the measurement of the earth's circumference as given by Eratosthenes; which, it will be recalled, was surprisingly close to the true circumference. The inhabited world Strabo considers a vast island surrounded on all sides by the ocean, and he concludes that it occupies about a third of the total circumference in the temperate zone. And in this connection he throws out the suggestion that there might thus be in the remaining space two or even more unknown inhabited worlds.

Strabo also takes for granted the division of the world into five zones. His discussion of this is of interest because it brings out the belief held at that time of the existence of a torrid zone uninhabitable because of excessive heat. Obviously, therefore, this would constitute an impassable barrier to exploration in that direction.

Nothing, perhaps, illustrates the dominant rôle of the Mediterranean Sea in the ancient world so well as the fact that even in Strabo's time this sea had no distinctive name. Strabo is aware of its importance to the countries around it and of the effect of its numerous arms and inlets in the development of the European civilizations. The Sea *was* the Mediterranean; and when it became necessary to specify it more definitely, Strabo is compelled to use such terms as the Inner Sea or Our Sea.

In the endeavor to reconstruct the view of the ancients with regard to the sea and its relation to the world, we have thus far found it necessary to go to the writings of the Greeks. Of the half-score or more names which have served as guides in our hasty survey of the development

of geographic knowledge during the nine or ten centuries from Homer to Strabo, all belong to those who drank at the fountains of Greek learning. For the state of knowledge regarding the sea in the first century, we must, however, turn to Pliny, a Roman writer.

About half a century after the appearance of Strabo's *Geography* Pliny published an encyclopedic work which he called *Historia Naturalis*. Literally this is translated as natural history, but more correctly perhaps it is to be rendered as history of nature; for that appears to have been Pliny's aim—to give a general view of all that was known of the world. No great advance in the knowledge of the Atlantic Ocean had taken place during the half century, though the Romans had become better acquainted with the sea around the British Islands. During this time, however, a considerable step forward was taken in navigation. Observing the regularity of the monsoon winds in the Indian Ocean, a venturesome Greek mariner steered a direct course from Arabia to India. This shortened the distance considerably, for the customary route was along the deeply indented coast. His example was followed and became the established practice at the time of Pliny.

Pliny was a great reader and his *Historia Naturalis* is frankly a compilation. Compared with the Greek geographers who preceded him—Eratosthenes and Strabo, for example—Pliny suffers, for he lacks their scientific comprehension. His writings are nevertheless of considerable importance, not only because they mirror the state of knowledge in the first century, but also because they constituted one of the principal sources of scientific information for many centuries following. He states as accepted views that the earth is spherical and that the inhabited part of it is completely surrounded by water. He explains that people may be living at the antipodes, and definitely ascribes the tides to the action of sun and moon.

He advances no theory to explain the connection between moon and tide, but the moon is credited with great potency as the following quotations from the *Historia Naturalis* make clear:

All seas are purified at the full moon; some also at stated periods. At Messina and Mylæ a refuse matter, like dung, is cast up on the shore, whence originated the story of the oxen of the sun having had their stable at that place. To what has been said above (not to omit anything with which I am acquainted) Aristotle adds, that no animal dies except when the tide is ebbing. The observation has been often made on the ocean of Gaul; but it has only been found true with respect to man.

Hence we may certainly conjecture, that the moon is not unjustly regarded as the star of our life. This it is that replenishes the earth; when she approaches it, she fills all bodies, while when she recedes, she empties them. From this cause it is that shell-fish grow with her increase, and that those animals which are without blood more particularly experience her influence; also, that the blood of man is increased or diminished in proportion to the quantity of her light; also, that the leaves and vegetables generally, as I shall describe in the proper place, feel her influence, her power penetrating all things.

We may conclude our survey of the knowledge of the ancients regarding the sea with the notice of the *Geography* of Ptolemy. Equally celebrated as astronomer, mathematician and geographer, his writings were of primary importance for many centuries. A native of Egypt, his works were written in Greek, the *Geography* appearing about the middle of the second century, or about three-quarters of a century after Pliny's *Historia Naturalis*.

It is important to study Ptolemy's views in some detail because of the very great influence of these views in later centuries. And at the very outset it must be noted that his *Geography* reflects the fact that he was more astronomer than geographer, the greater part of it being taken up by a table of the latitudes and longitudes of the more important

places of the then known world. As astronomer, Ptolemy was convinced that an accurate map of the world could be drawn only on the basis of a knowledge of the latitudes and longitudes of the principal places.

But, as has already been pointed out, the ancient determinations of latitude, and more particularly of longitude, were very crude because of the lack of instruments for precise measurements. For his determinations of latitude and longitude Ptolemy had to rely in large part on such rough methods as the time taken by travelers in journeying from one place to another. This is to be borne in mind in considering Ptolemy's map of the world, since this was constructed on the basis of the latitudes and longitudes of his table.

To Ptolemy is traced the first use of the technical terms, parallels and meridians. On his map he took as prime or zero meridian the one going through the Fortunate Islands on the assumption that these lay farther west than any part of Europe or Africa. A comparison of his map with a modern map will bring to light numerous errors in the location of places, but two other matters are of greater interest for our purpose.

In the first place it is to be noted that Ptolemy makes of the Indian Ocean a closed sea, assuming a Terra Incognita lying to the south and connecting with the African land mass. But what is even more striking is the vast extent of the continental land mass of Europe and Asia from west to east in the lower temperate latitudes. In these latitudes, from the western coast of Europe to the eastern limits of India shown by Ptolemy on his map, the land stretches for about 180° of longitude or half the circumference of the earth. A glance at a modern map shows how grossly this is exaggerated, for in these latitudes the land mass extends but one-third the circumference.

This exaggerated east and west extension of the known

world harks back to a time much earlier than Ptolemy. Various considerations had conspired to bring about the view among Greek geographers that the length of the inhabited world, in the east and west direction, was more than twice its width in the north and south direction. And with no ready means for even approximately correct determinations of longitude, Ptolemy was compelled to follow the accepted views with regard to the length of the inhabited world. As a result of this view, the distance from Europe westward to India was considered as much less than it actually is.

It happens, too, that another error at that time contributed to bring about a still greater exaggeration of the nearness of Europe to India across the Atlantic. One of the geographers on whom Ptolemy relied for a great deal of his geographical data—a certain Marinus of Tyre—had adopted Posidonius' estimate of 18,000 miles for the circumference of the earth rather than the larger one of Eratosthenes, which we know was more nearly correct. Ptolemy followed Marinus in this matter, so that a degree of longitude represented a distance about twenty-five per cent less than it actually is. These two errors led to the view that westward across the Atlantic lay India at a distance much less than is actually the case. And this view was of profound importance in the accidental discovery of the New World.

CHAPTER II

THE CROSSING OF THE OCEAN

THE scientific activity in the Mediterranean world, which with respect to the sea was sketched briefly in the preceding chapter, was, after the second century A.D., followed by a period of sterility. In this regard Ptolemy's *Geography* may be taken as marking a turning point. For after Ptolemy begins the intellectual decline in Europe which reached its nadir in the Dark Ages from the fifth to the tenth centuries. The gradual disintegration of the Roman Empire was accompanied by the closing up of established avenues of communication, with the inevitable consequence of a deterioration of the store of knowledge concerning distant regions. And with the conversion of pagan Rome, the conception of the world which had grown up as a result of the scientific activity of Greek and Roman geographers gave way to one based largely on fanciful interpretations of Scriptural phrases.

During this time, to be sure, there might be found—here and there—some scholarly churchman still familiar with the remains of ancient learning. But the descriptions of the world were now chiefly by those writing in a theological spirit. As illustrative of these, the *Christian Topography* of Cosmas Indicopleustes may be cited. Cosmas lived in the sixth century and in his earlier years had traveled extensively, whence his nickname "Indicopleustes" or the Indian traveler. Later he became a monk and about the middle of the sixth century wrote his *Christian Topography,* the chief object of which was to denounce the false

and heathen doctrine that the earth is a sphere. Cosmas proves, on Scriptural grounds, that the earth is a rectangular plane, in the center of which is the inhabited portion of the earth. Night and day come from the sun revolving round a conical mountain, the varying length of the day arising from the fact that in winter the sun revolves around the base of the mountain, while in summer it revolves around the summit.

With the eleventh century, however, a period of more critical ideas is ushered in. At this time western Europe felt the vivifying influence of Arab thought and learning which had not lost contact with the earlier Greek and Roman knowledge. This is the period, too, of the Crusades. Europe and Asia were becoming better known than before, and no longer was one wholly dependent for his conception of the physical world on a mixture of Scripture and little-understood remnants of ancient learning. Through the Arabs the Middle Ages received anew the learning of the Greeks, for in western Europe Greek was little known during this period. Ptolemy's *Geography*, for example, was comparatively little known until it was rendered into Latin in A.D. 1410.

It was during this period also that the mariner's compass came into use in Europe. This permitted voyages on the high seas, and led to the increased production of the so-called Portolano charts of the Middle Ages. These are maps based on estimated directions and distances between the principal ports or capes of a region. They are not based on latitudes or longitudes, their most characteristic feature being systems of lines radiating from a number of centers. Originally intended for the mariner navigating the Mediterranean and neighboring coasts of the Atlantic, these Portolano charts were finally extended to cover the whole of the then known world.

Passing mention must here be made of the voyages of

the Vikings. These northern sea rovers, about the middle of the eighth century, began a series of piratical raids upon the coasts of Europe, and in the course of the next century Scandinavian kingdoms were established in Ireland and in England. In the art of shipbuilding the Vikings were ahead of the other European peoples and we find them making voyages into Arctic waters. Iceland was colonized by Norsemen in the latter decades of the ninth century, and in Greenland, too, Norse settlements were established. It was from Greenland that Leif the Lucky set sail to the west in the year 1000 and came upon a land of forests and wheat and grapes which he called Vinland—apparently discovering the continent of America nearly 500 years before Columbus.

Striking as were the achievements of the Vikings, they were nevertheless of but very slight influence on the development of European knowledge. So far removed were Greenland and Iceland from the centers of European learning that only vague reports of the discovery of land in the western sea by Norsemen reached western Europe. Moreover, belief in the existence of mysterious islands in the sea to the west was widespread in the Middle Ages, and this particular discovery would have bulked no larger than generally accepted reports of other legendary isles. Indeed, it was only at a very much later period—within comparatively recent times in fact—that the story of the voyages of the Vikings became known throughout Europe. Even after the Viking age western Europe still regarded India as lying directly across the intervening waters of the Atlantic.

A considerable extension of the geographic horizon occurred after the middle of the thirteenth century with the opening up of direct communication from Latin Europe to the Far East—to India and to China, or Cathay, as it was then known. By the middle of the thirteenth century

Tartar conquests had consolidated an empire stretching from Europe across Asia to the Pacific. The Tartars were tolerant of all creeds and soon European merchants, missionaries and political emissaries moved unhampered from west to east. And for a hundred years this road to Cathay was kept open to the traveler.

Of the travelers of this period, the best known is Marco Polo. In 1271, as a lad of seventeen, Marco accompanied his father Nicolo and his uncle Maffeo Polo on a journey from Venice to the court of Kublai Khan in China. The elder Polos were Venetian merchants who some ten years before had gone on a trading expedition which eventually brought them to the Great Khan himself. They were the first Europeans he had seen, and after welcoming them warmly listened to all they told him of the West. Finally he sent them back on a mission to the Pope, asking for a hundred men of learning to preach to his Tartars.

On their return journey to the East, which began in the fall of 1271, only Marco accompanied them. Two Dominicans, who were to constitute the men of learning to preach to the Tartars, left the Polos almost at the very outset. For three and a half years the travelers journeyed eastward, reaching the court of the Great Khan early in 1275. Then followed seventeen years in the service of Kublai, Marco especially finding favor and being employed on missions which took him into various parts of the Great Khan's dominions. Everywhere he went, he observed the land and the people, making notes of what he saw.

In 1292 the Polos began their homeward journey, arriving in Venice in 1295, and four years later Marco Polo's *Book of Travels* appeared. This revealed to Europe the extent and wealth of the East, and for nearly five decades thereafter the European merchant and trader had direct access to the riches of Cathay and the Indies. But by the middle of the fourteenth century direct trade came to an

end, for by this time Central Asia had become converted to Islam, which threw a barrier across the trade routes that for a hundred years had been open.

It is not without significance that Columbus had a copy of Marco Polo's book. And that he had read it with care is evident from the fact that on many pages of this copy are notes in the handwriting of the great discoverer. The influence of Polo's travels found reflection also in a more correct representation of the Far East on charts and maps. In the so-called Catalan map, which is a Portolano map dating from the year 1375, Cathay is shown in its true position in southeastern Asia, and for the first time India is represented approximately correct as regards outline and position.

In Polo's narrative appears a description of Zipungu or Japan—an island pictured by him as rich in gold and precious stones. Indeed, Polo describes much of the East in glowing colors. Other travelers' tales of the thirteenth and fourteenth centuries were full of even more fabulous stories of the riches of the East. And for the reader of that time it was impossible to distinguish, in such tales, the true from the false. To western Europe of the Middle Ages the countries of the East were glamorous lands of fabulous wealth.

The expansion in trade of this period brought about a revival of town life throughout Europe, the most splendid development of which took place in Italy. Great trade seaports arose in Venice and Genoa, their ships trading throughout the Mediterranean and out in the Atlantic to the German towns of the Hanseatic League. New peoples were taking to the seas and considerable progress in seamanship and shipbuilding marked the fourteenth and fifteenth centuries.

This active development of maritime trade and commerce undoubtedly brought up now and again the question of the

possibility of a new route to the East—via the sea. And the closing up of the direct trade routes to the East, after the middle of the fourteenth century, gave greater point to this question. As early as the year 1291—when East and West were still in direct communication across the Eurasian land routes—an attempt was made to reach India by sea. In that year an expedition set out from Genoa, and, after passing out of the Mediterranean, turned south down the coast of Morocco. Here all trace of it is lost; but what makes it of significance is the avowed purpose of the leaders "to go by sea to the regions of India and bring back useful things for trade."

After the middle of the fourteenth century the off-lying islands in the Atlantic—the Canaries, the Madeiras and even the Azores—became known. And with the fifteenth century the exploration of the sea enters a period of vigorous enterprise, the stimulus coming from the efforts of Prince Henry of Portugal to explore the route down the Atlantic coast of Africa. Beginning in the second decade of the century, Prince Henry sent out, in turn, a number of expeditions with the object of rounding Cape Bojador, which at that time constituted the southernmost known outpost of the sea along the coast of Africa.

From the Strait of Gibraltar to Cape Bojador the coast stretches for nearly a thousand miles, and a glance at a map of Africa will show why it took so many years to pass beyond this point. The trend of the coast is southwesterly—away from the known and out into the unknown Atlantic. A little north of Bojador the channel between the Canaries and the coast becomes funnel shaped, thereby helping to increase the strength of the currents. The surf is exceedingly heavy and landing at most places is difficult. Viewed from the ocean, Cape Bojador appears to terminate in a chain of rocks over the protruding heads of which the sea breaks heavily. In fact the three-hundred-mile

stretch just north of Bojador still constitutes the most dangerous part of that thousand miles of coast line.

It was only in 1434 that Bojador was passed, and the doubling of this cape must be regarded as an event of considerable importance. For not only with the real perils of the sea did the seamen of that time have to contend; much more terrible were the terrors with which from ancient times the unknown sea had been invested, and from which mankind had not yet freed itself. The crossing of this seemingly impassable part of the sea was an omen, therefore, of still greater conquests that were to come.

After this time progress was, indeed, comparatively rapid; for the added incentive of great profit aided the cause of maritime exploration. Soon after the rounding of Cape Bojador a Portuguese expedition brought back gold dust and slaves from the territory beyond. Steadily, now, Portuguese exploration advances farther southward. In 1473 the equator is passed, and in 1487 Bartholomew Diaz rounds the Cape of Good Hope. The eastward sea route to the Indies now lies open, and the ocean is almost crossed. But a delay of about ten years on the part of the Portuguese gives the honor of the first crossing to a daring navigator from Genoa. When in 1497 Vasco da Gama sailed from Lisbon and reached India by the southeastern route, Christopher Columbus five years previously had set a new milepost in the achievement of mankind by crossing the ocean, sailing due west from Europe.

The idea of crossing the ocean by sailing toward the setting sun was one Columbus had lived with for a number of years. His views of the distribution of land and sea were molded especially by Marco Polo's *Travels* and by the *Imago Mundi* of Cardinal Pierre d'Ailly. The latter wrote a number of geographical treatises in the early years of the fifteenth century which are marked by great learning. He took the sphericity of the earth for granted and

regarded the sea between India and Spain as of small extent, quoting the assertion of the Roman poet Seneca that with a fair wind this sea could be traversed in a few days.

For a number of years Columbus had tried to secure financial support for his plan of reaching Asia by sailing across the Atlantic. In this plan manifestly, the extent of the sea to be traversed was a matter of prime importance. But to solve this problem it was necessary to assign numerical values to the circumference of the earth and to the eastward extension of Asia. It happens that a number of circumstances conspired to lead Columbus to take the circumference of the earth as between 18,000 and 19,000 miles. This greatly reduced circumference of the earth, it will be recalled, was the one accepted by Ptolemy, and his authority now carried great weight. It found support, furthermore, in some measurements made by Arab astronomers in the ninth century.

This error in the circumference of the earth of itself reduced the extent of the ocean between Europe and Asia by 25 per cent. But a still further reduction resulted from the extreme eastward extension assigned by Columbus to the coast of Asia. This extreme eastward extension of Asia harked back to the geographers of ancient times, and appeared to find confirmation in the writings of the travelers of the preceding centuries. All in all, the data which Columbus made use of placed the Indies but half the true distance across the sea from Europe.

The story of Columbus' eventful journey need be touched here only in briefest outline. Starting out from Spain with three small ships in August of 1492, he made first for the Canaries; and from there, on the sixth of September the little fleet set out into the unknown sea. For thirty-five days they were out of sight of land, sailing steadily in the wake of the setting sun. During the journey Columbus had to quiet the fears of his sailors on various

occasions, for a number of things happened which frightened them. The now familiar fact of the variation of the compass—that the compass needle points in somewhat different directions at different places—was unknown at that time. And when after a week they came into a region where the failure of the compass to point true north became apparent, it brought slumbering fears to the surface and lent an air of credibility to the terrifying tales of the western sea. During the second week a meteor was seen to fall into the sea, and several days later they entered an area which, so far as the eye could reach, was covered by floating patches of seaweed—the area we know as the Sargasso Sèa. Wind and current were prevailingly from the east—helpful, to be sure, in the journey westward; but would they be able to make headway against these and return to Spain? All fears, however, were forgotten when on the twelfth of October one of the Bahama Islands was sighted and the ocean was crossed.

Which island of the group it was that Columbus first sighted is still a matter of controversy, constituting the so-called problem of the landfall of Columbus. On landing he named the island San Salvador, but it has not since been definitely identified. For the honor no less than five widely separated islands of the Bahama group have at different times contended, the claims of each being urged by various authorities. Here, however, it is unnecessary to enter the controversy, for it is the crossing of the ocean that constitutes the most important fact.

Columbus naturally believed he had succeeded in reaching Asiatic waters; and after cruising about the various islands for nearly three months, he started on his return voyage to Europe, arriving at the Azores in a month. But it is to be observed that he did not return by the same route that he had come. The two routes are shown in Figure 1, the route followed on the outward journey being

indicated by the dashed line while the return route is indicated by the dot-and-dash line.

Why Columbus did not follow the same track on his return journey, and why he had gone south to the Canaries instead of sailing due west from Spain on his outward journey, we can only conjecture. But if we study the winds and currents of the Atlantic we find that the latitude of the Canaries defines the region of the northeast trade winds. Wind and current here help a sailing vessel on its

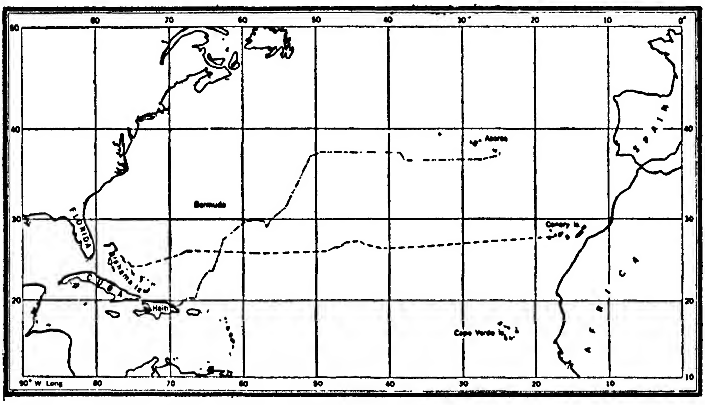

FIG. 1.—SKETCH MAP SHOWING WESTWARD AND EASTWARD ROUTES OF COLUMBUS, FIRST JOURNEY

westward journey. The latitude of the Azores, however, defines a region of prevailing westerly winds. It is a striking fact, therefore, that in both cases he chose the most favorable route. Indeed, even now, after four centuries of experience the routes of sailing vessels are much the same as those used by Columbus on his first voyage. Was this choice of routes but a happy chance on the part of Columbus or does it represent splendid seamanship based on a careful study of all available information at that time?

The news of the successful crossing of the ocean gave greater impetus to oceanic exploration. Columbus himself

made three other voyages across the Atlantic; Vasco da Gama in 1497 reached India by sailing down the coast of Africa and striking out across the Indian Ocean; in 1513 Balboa saw stretching westward before him the Pacific Ocean, and in 1519 Ferdinand Magellan started on the voyage which, in a sense, consolidated the achievements of his fellow discoverers. With five vessels he left Spain on a westward voyage; and after nearly three years one of these vessels arrived in Spain, having accomplished for the first time in man's life the circumnavigation of the earth.

Something of what it cost in human effort to carry through an expedition like Magellan's may be sensed even from a bare recital of the facts. Starting with five ships and nearly three hundred men, he steered southwest until South America was sighted, and then sailed down this coast looking for a passage to the Pacific. The first winter the expedition spent on the coast of Patagonia, during which time one of the vessels was lost. From here they sailed southward again, discovering the passage to the Pacific now called the Strait of Magellan. One vessel here deserted and returned to Spain, but the other three finally came out into the Pacific, and then for three months the expedition sailed northwesterly before striking the Ladrone Islands. During this time the explorers had no fresh provisions and but little water so that they were ravaged by scurvy. Going on to the Philippines, Magellan was killed in a fight with the natives and other members of the expedition were murdered. The survivors then burned one of the three vessels and with the other two proceeded to the Moluccas. Here one of the vessels became leaky and stayed behind with her crew, while the other vessel proceeded to Europe alone, reaching Spain again after an absence of three years, with thirty-one of the nearly three hundred that had started.

The consequences of the memorable voyages of the three

decades from 1492 to 1522 were far-reaching. Columbus brought a new world within the bounds of civilization; da Gama opened up the long-wished-for sea route to the Indies; and Magellan revealed the true extent of earth and sea. Of themselves these were achievements of the first magnitude. But this was not all these intrepid men of the sea did. For in a true sense they discovered the ocean. No longer was the sea to constitute a barrier to man: with its successful crossing it was to become a highway for commerce and trade, a channel for the exchange of knowledge and ideas. From time immemorial mankind had invested the open sea with all sorts of terrors. By their voyages the great explorers swept the oceans clear of these imaginary terrors and opened wide horizons for humanity.

These discoveries, it must be noted, came at an auspicious time. The intellectual awakening of the Renaissance was bearing fruit in a Europe of renewed vigor and capacity. The revival of learning made the works of the great Greek geographers known. Paper for books had become abundant and cheap by the end of the fourteenth century; and before the second half of the fifteenth century was well on its way, the achievement of printing made possible the rapid spread of knowledge by means of the printed page.

With the crossing of the three great oceans it was possible to construct a map of the world that, in its larger features at least, corresponded to the actual distribution of land and sea. And by the middle of the sixteenth century we find such maps being made. Succeeding explorers revealed the more intimate details of the sea, and some of these voyages of exploration we will have to notice later, especially in connection with the search for the Northwest Passage and the attainment of the poles. Now, however, it will be of advantage to consider the question of legendary isles, belief in which persisted to the times of the great explorations, and even after.

CHAPTER III

LEGENDARY ISLES

THE Middle Ages inherited from the ancients the belief in the existence of mysterious isles out in the Atlantic. From the Greek poets came stories of the Islands of the Blessed, the paradise of departed heroes. Islands in the sea were also associated with such mythical tales as the labors of Hercules. Later, when the off-lying Atlantic islands—the Canaries and the Madeiras—became known to the Roman world, the glowing accounts of land and climate led to their designation as the *Insulæ Fortunatæ*, the Fortunate Islands.

While the mythology of the ancients was not wanting in stories of islands serving as abodes of evil spirits, as a general rule the legendary isles were pictured as lands of desire. And as such the medieval world regarded them. When, during the Dark Ages, knowledge of the Atlantic islands was lost, vague memories of Fortunate Islands remained. These persisting memories helped to assimilate into the European folklore the pagan beliefs in legendary islands bequeathed by the ancients. Out of this folklore came the material for clothing various tales of the sea with mythical garments, and so arose a body of lore regarding islands in the western sea.

It may be noted that the belief in the existence of these islands was not without influence in the voyages of discovery. As soon as western Europe took to the sea it was natural that attempts at finding such islands should be made. Furthermore, as possible stopping places such islands were

regarded as making practicable a westward voyage to India across the Atlantic Ocean. And it may be noted, too, that the belief in these islands was widespread, being shared as well by mariner and geographer. On the maps of the fourteenth, fifteenth and sixteenth centuries a number of islands are shown which later explorations proved to be myths.

Of the various legendary islands, we need here consider but three, namely, St. Brandan's Island, Antillia or the Isle of the Seven Cities, and Atlantis.

The stories of St. Brandan's Island relate to the marvelous adventures of the Irish abbot St. Brandan, who lived in the sixth century. He is represented in these stories as undertaking a voyage by sea during which he discovers various islands and sees wondrous sights. On one island there were a great number of white sheep bigger than oxen. Another island begins to move when a fire is built on it, and turns out to be an enormous fish. His ship also passes the rock on which Judas Iscariot has occasional respite from his torments.

One of the islands which St. Brandan visits, he finds possessed of a mild and delightful climate and a fruitful soil—a veritable Land of Promise blessed with an abundance of all good things. To this island the name of St. Brandan has been attached. On the maps of the thirteenth and following centuries St. Brandan's Island is shown in various locations. Prior to the discovery of America it is generally placed in the vicinity of the Canaries or the Madeiras. Later it is located farther west and is so represented on a map dating as late as the latter half of the sixteenth century.

Just what basis of fact underlies the story of St. Brandan's Island? Stripped of its fanciful and mythical elements, it purports to be the record of a voyage to some remote island in the Atlantic having a delightful climate.

Quite possibly the story may have as basis an actual voyage to some pleasant island of the Canary or Madeira group. Undoubtedly, too, this story of an island out in the western sea, blessed with all good things, harks back to the mythical Islands of the Blessed of the ancients—lands of the heart's desire, where life is free from the common cares and ills.

Attempts have been made to connect the story of St. Brandan's Island with pre-Columbian voyages to America. Certain legends and sagas appear to point to Irish voyages to Iceland and to a large country to the westward, some time before the eleventh century. On the basis of these legends the story of St. Brandan's Island is taken as embodying the record of some such voyage. But these attempts to connect St. Brandan's Island with America are far from convincing.

The stories of Antillia or the Isle of the Seven Cities have much in common with those of St. Brandan's Island. They go back to the eighth century when the Moors descended on Spain and overran the Iberian Peninsula, and tell of the flight of Christian refugees who, under the leadership of seven bishops, set out on a voyage westward and reached the island of Antillia. Here a model community of seven cities, each under the rule of a bishop, is established. Like St. Brandan's Island, Antillia is located in different places on different maps but generally it is out in the open Atlantic.

At the time of Columbus Antillia appears to have been still widely accepted, and reports were current of ships having sighted the island when driven out of their course by exceptional storms. It appears on maps as late as the latter decades of the sixteenth century, but after this time it disappears.

Of all the legendary islands Atlantis is at once the oldest and the one which has persisted for the longest

time—down to the present time in fact. The maritime explorations following the crossing of the ocean swept the Atlantic clear of the numerous islands with which a more credulous time had dotted it. But Atlantis is represented as having sunk beneath the waves many centuries ago. Hence the belief in its former existence was in no way affected by the proof of the legendary character of the other islands which ancient and medieval tradition had located in the Atlantic. and it still constitutes a problem of the sea.

The story of Atlantis as we know it goes back twenty-three centuries to the Greek philosopher Plato, who relates it in one of his dialogues. Plato represents the story as having been told to Solon of Athens, one hundred and fifty years previously, by an old Egyptian priest who mentions records dating back nine thousand years which tell of Atlantis, a large island in the sea beyond the Pillars of Hercules. The Egyptian priest, in Plato's narrative, tells of "kings of amazing power" reigning on the Island Atlantis, and he then goes on with its history in the following words:

> All this power was once upon a time united in order by a single blow to subjugate our country, your own, and all the peoples living on the hither side of the strait. It was then that the strength and courage of Athens blazed forth. By the valor of her soldiers and their superiority in the military art, Athens was supreme among the Hellenes; but, the latter having been forced to abandon her, alone she braved the frightful danger, stopped the invasion, piled victory upon victory, preserved from slavery nations still free, and restored to complete independence all those who, like ourselves, live on this side of the Pillars of Hercules. Later, with great earthquakes and inundations, in a single day and one fatal night, all who had been warriors against you were swallowed up. The Island of Atlantis disappeared beneath the sea. Since that time the sea in these quarters has become unnavigable; vessels can not pass there because of the sands which extend over the site of the buried isle.

In another of his dialogues Plato gives a somewhat detailed description of Atlantis. After a recital of the fabulous origin of the country follows an account of this island empire commanding the sea and possessed of fertile soil and delightful climate, of populous villages dotting its mountain sides, of a city of magnificent palaces and temples built of stone, of mines rich in all the metals. And all this might and splendor vanishes in a day and a night as if by the wrath of the gods.

Plato's story of Atlantis is one of great dramatic appeal. Here were a people of wealth and power. They, too, had wrested from a reluctant Nature her secrets and made her pay tribute to their comfort. They, too, had learned to fashion things of grace and beauty and power. And is this to be the end of all striving—to be swept from the face of the earth in a single day and night? Even the scientist is not unmoved by the thought of the last night of Atlantis. A well-known French geologist pictures it in these words:

The young men have all departed for the war, beyond the islands of the Levant and the distant Pillars of Hercules; those who remain, men of mature age, women, children, old men, and priests, anxiously question the marine horizon, hoping there to see the first sails appearing, heralds of the warriors' return. But to-night the horizon is dark and vacant. How shadowy the sea grows; how threatening is the sky so overcast! The earth for some days has shuddered and trembled. The sun seems rent asunder, here and there exhaling fiery vapors. It is even reported that some of the mountain craters have opened, whence smoke and flames belch forth and stones and ashes are hurled into the air. Now on all sides a warm gray powder is raining down. Night has quite fallen, fearful darkness; nothing can be seen without lighted torches. Suddenly seized with blind terror, the multitude rushes into the temples; but lo! even the temples crumble, while the sea advances and invades the shore, its cruel clamor rising loud above all other noise. What takes place might indeed be the Divine wrath. Then quiet reigns; no longer

are there either mountains or shores; no longer anything save the restless sea, asleep under the tropic sky, with its stars unnumbered.[1]

Is the story of Atlantis a literary invention, or does it embody in a more or less legendary form an actual story of the sea? Does this story owe its strong appeal through the centuries wholly to the literary genius of Plato, or does it awaken some vague subconscious reminiscences of the catastrophic end of a great nation? Both sides of the question have been vigorously maintained ever since Plato first gave the story to the world.

Those who hold to the fictional character of Atlantis stress the fact that before Plato this story, which purports to record an event of striking and unusual character that happened many years before, is apparently unknown. Were such a catastrophe to have occurred, wouldn't mention of it be found in other and earlier writers? Students of Plato appear in the main to be agreed that in its context Atlantis bears the stamp of literary creation.

On the geological side, too, there are objections to the disappearance of a large island mass beneath the sea. Earthquakes and tidal waves with large attendant loss of life are known. Changes in local relative elevation of land to sea likewise are known. And that small islands may have disappeared beneath the waves is quite probable. But the total disappearance of a large area within the life period of civilized man on earth is altogether unknown and quite improbable.

Despite all these objections, belief in the former existence of Atlantis has persisted. During the Middle Ages such belief was in consonance with accepted views. Cataclysmic ends to those who transgressed Divine law were in

[1] Pierre Termier, "Atlantis," in *Annual Report of the Smithsonian Institution for the Year 1915,* p. 234.

keeping with the theological teaching of the time. Numerous legendary islands were believed to lie out in the Atlantic and this but fortified the belief in a former Atlantis.

There are not wanting cogent reasons on the part of those who hold to the essential truth of Plato's story. Entirely apart from the efforts of the more credulous, who find in Atlantis a haven for all sorts of vagaries, there are scholars who maintain that all myths embody some actual occurrences which in the telling and retelling through the ages have undoubtedly become greatly distorted and much exaggerated. Of this type they hold Atlantis to be. We know that earlier civilizations have flourished and decayed. May not the story of Atlantis tell in legendary form the fate of one of these bygone civilizations?

Out in the Atlantic, west of the Pillars of Hercules, the Azore Islands rise from the depths of the sea. May not these islands be but the mountain peaks of a much greater island that now lies at the bottom of the sea? Also in the Atlantic, but southwest of the entrance to the Mediterranean lie the Canary and Cape Verde islands. Here again we may ask whether these do not represent the remnants of a more extensive land mass which was the home of a populous and civilized nation.

A carefully reasoned statement of the case for the lost Atlantis out in the Atlantic is given by the French geologist Pierre Termier,[2] from whose article was quoted the excerpt above. In this article he marshals geological and zoölogical evidence in favor of the thesis. In attempting to unravel the history of the earth the geologist comes across facts which point to the existence, at some previous time, of a large land mass in the Atlantic. But this must be put at a period so very much earlier than the possible appearance

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[2] *Loc. cit.*, pp. 219-234.

of civilized man, that it is of no help to those maintaining the former existence of Atlantis.

On the assumption that Plato transmits, albeit in legendary form, an episode in the life of mankind, recent attempts at the solution of the problem have turned in the direction of identifying Atlantis with the site of some former historic civilization. Thus, when the archeologist unearthed evidences of a splendid bygone civilization on the island of Crete, one student of the problem thought that this island in the Mediterranean tallied remarkably well with Plato's description of Atlantis. According to another student, ancient Tartessus—the Tarshish of Biblical times—presents many features that resemble closely the description of Atlantis. This would place Atlantis on the Atlantic coast of Spain, for it is here, in the vicinity of Cadiz, that Tartessus is supposed to have flourished. It is to be observed, however, that while these solutions of the problem have been presented by competent workers in the field, they have not met the objections urged by other authorities and neither solution has been generally accepted.

A very plausible solution has recently been offered by the German geographer, Paul Borchardt. He places the site of Atlantis within the Mediterranean in the region of the Gulf of Gabes on the coast of Tunis. Many facts indicate that this region was at one time the seat of an extended civilization which was destroyed by some convulsion of nature like an earthquake. By a painstaking interpretation of the text of Plato's story in the light of the geographic knowledge of that time, Borchardt makes out a strong case for this location.

It is to be remembered that in the story of Atlantis we have Egyptian material translated into ancient Greek, which is then again translated into modern languages. We are far removed from the geographic conceptions of these ancient peoples. It appears, for example, that the word

"island" by which Atlantis is described may not have been used in the strict sense that we employ it nowadays. And while there is no question that the term, Pillars of Hercules, had finally come to mean the Strait of Gibraltar, in earlier times it may have been a more general term applied to places marked by a temple of Hercules. Such temples were set up as symbols of the god of maritime traders and were distinguished by two columns or pillars. In translating from Egyptian into ancient Greek and from the latter into modern tongues, it is clear that somewhat changed meanings may have been attached to a number of words. It is not at all certain that Plato meant that Atlantis lay outside the Mediterranean, which hitherto has been the generally accepted location.

In regard to chronology, too, it is not to be forgotten that many of the ancient peoples made use of the moon rather than the sun in keeping track of time. The nine thousand years which Plato's Egyptian priest mentioned may not improbably refer to lunar months which would make the period 750 years. Plato lived about 400 B.C. Adding the 150 years that had elapsed since the telling of the story by the Egyptian priest we arrive at 1300 B.C. as the probable date of the destruction of Atlantis, a date which fits in well with the time when the region of the Gulf of Gabes may have been the seat of an extended civilization.

It cannot yet be said that the problem of Atlantis has been solved. It is significant, however, that competent students of the problem are more inclined to view Plato's story as based on fact, notwithstanding the admixture of mythical and fabulous elements. Furthermore, it is recognized that Plato's version may have been shaped by its author's need for pointing a moral. It is to be noted, too, that the more recent views reduce the size of the island which suffered destruction, and place it within the Mediterranean, rather than out in the Atlantic.

With uncritical and fanciful solutions of the problem of Atlantis we need here not concern ourselves. Mention should, however, be made of the fact that Plato's statement "since that time the sea in those quarters has become unnavigable," has sometimes been taken to refer to the Sargasso Sea, which not so long ago was thought to be so thickly strewn with gulfweed as to impede the passage of vessels. And on that flimsy foundation was reared a full-blown theory that beneath the waters of the Sargasso Sea lies the lost Atlantis.

CHAPTER IV

THE SARGASSO SEA

In the very heart of the Atlantic Ocean, midway between the Bahamas and the Azores, lies the great body of water known as the Sargasso Sea. The designation of this part of the Atlantic as a "Sea" is at first glance something of a paradox, for no land boundaries of any kind mark it off from the rest of the open ocean. There is, however, justification for the designation in the fact that the characteristics of this tract of water are so marked as to confer upon it a distinct individuality.

Its name, which is derived from the Portuguese word for seaweed, it owes to the prevalence of seaweed or gulfweed floating over its surface. Legend and myth have covered this area with islands of thickly matted seaweed many miles in extent, peopled it with strange monsters and made of it the graveyard of missing ships. Even now it is not uncommon to find it stated in serious publications that in certain parts the Sargasso Sea is so thickly matted over with seaweed that vessels passing through are much retarded in their speed.

Not only is it differentiated from the rest of the Atlantic Ocean by the prevalence of gulfweed on its surface, but its waters likewise exhibit distinctive characteristics. Surrounded by great current systems which include the mighty Gulf Stream, the waters of the Sargasso Sea are relatively motionless. It is further marked off by the exceptionally high salinity and high temperature of its water as well as by its unusually deep blue color—rivaling indeed the blue-

ness of the sunny skies above it. And coupled with this is great transparency. Here a white disk about six feet in diameter was clearly seen with the naked eye when lowered two hundred feet below the surface.

Whether the Sargasso Sea was known prior to the discovery of America is still an open question. There appear to be grounds for believing that those remarkably hardy navigators of ancient times, the Phœnicians, were acquainted with it. Before the beginning of the Christian era there are references to the sea west of the Pillars of Hercules, certain parts of which are represented as being unnavigable because of seaweed. And there is a record of the fact that a Portuguese sailor told Columbus prior to his eventful journey that one of the obstacles to be overcome in the westward voyage to India was the grasses.

It appears not at all improbable that some vague knowledge of this sea existed before 1492. To Columbus, however, must be credited its discovery and the first authentic notice of the occurrence of gulfweed in this region. On his first voyage westward he encountered gulfweed for a number of days; and likewise on his return journey. In his log we find that the great navigator carefully recorded the occurrence of the gulfweed.

Viewed from the small vessels which Columbus and the other navigators of that time sailed across the Sargasso Sea to the New World, the patches of gulfweed undoubtedly looked vastly more formidable than they really were. This region is one of light winds; hence a sailing vessel here made slow progress. It is therefore little wonder that stories of widespreading meadows of thickly matted gulfweed which seriously impeded the progress of vessels became current. These stories, it is of interest to note, originated not with Columbus, but with his followers. Columbus himself records the occurrence of the gulfweed in a characteristically accurate manner.

The belief in the existence of great areas of thickly matted gulfweed in the Sargasso Sea has persisted down to the present time. But with the accumulation of carefully recorded observations this has been proven to have no basis in fact. The gulfweed occurs in scattered masses up to one hundred feet in diameter, although patches covering an acre or even a little more have been seen occasionally. Sometimes under the action of the wind, long strips of gulfweed are formed which follow the direction of the wind. But it has been definitely proven that there are no islands of gulfweed miles in extent, and that it is nowhere so dense as to interfere with the movements of a ship.

At times the patches of gulfweed range themselves in such fashion as to give the appearance of river banks, the clear water between these banks heightening the illusion of the river-like appearance. Captain C. C. Dixon, who has traversed the Sargasso Sea many times, describes these phantom rivers in the following words:

When in a small boat the winding bands of water free from weed look exactly like a river. Through the low elevation of the eye, the breaks between the patches of weed at the sides are hardly noticeable, and at dusk they assume an appearance of solidity that makes the clear water appear a very real river, and it requires a distinct effort of the will to steer the boat into one of the banks even if you really know it consists of loose weed. But when you do you will be conscious of no change except that of passing from clear water to where the surface was weed-strewn, for it offers not the slightest resistance; in fact, it is doubtful if it ever really touches the boat, the slight bow wave of the slowly moving boat is sufficient to open a clear passage. The length and general direction of these slightly winding "rivers" appear quite fixed, and steering along one you might be under the impression that you were steering in some definite direction. But they are in truth phantom rivers. If your attention is diverted for a moment or two and you look around you find yourself steering into the bank and hurriedly alter your

course thinking you have not been watching the steering; but if you have a compass or the day is not overcast you will find it is the river that has closed and opened out in a new direction.[1]

What explains the decided individuality of this great body of deep water lying out in the open ocean? It is upon a vast stage—measured in millions of square miles—that the activities of the Sargasso Sea take place. Many details are still unknown, and these can come only as the result of patient oceanographic research. Enough, however, is known to give an understanding of the forces and factors that give rise to the larger distinguishing features of the Sargasso Sea.

Primarily the Sargasso Sea owes its existence to the ocean currents that surround it. If we glance at a map showing the circulation in the North Atlantic Ocean, it will be seen that three great current systems bound the Sargasso Sea. On the south is the North Equatorial Current flowing westward, on the west and north is the Gulf Stream flowing northward and then eastward and on the east is the Canary Current flowing southward. These currents thus make a closed circuit about the Sargasso Sea, and within the shelter of this the waters of the Sargasso Sea have developed a distinct individuality of their own.

The high salinity of the water in the Sargasso Sea is due to the coöperation of a number of factors. Situated at a considerable distance from any coast, there is no dilution by the less saline waters poured into the ocean by continental rivers. Nor is such water brought into the region by any currents, for the circulation of the sea is about the Sargasso Sea and not into it. Freedom from melting ice likewise removes a factor that tends to lower salinity. Moreover the region is one of relatively high temperature, favoring evaporation and therefore increased salinity of the

[1] *The Geographical Journal,* November, 1925, p. 439.

water. This latter factor is further augmented by the relatively high percentage of sunny days.

Obviously, a number of the factors that bring about the high salinity of the water in the Sargasso Sea are also instrumental in bringing about a relatively high temperature of the water. Its position in lower latitudes, coupled with freedom from strong currents, permits the sunny skies to maintain a heightened temperature of the water. Furthermore, it is to be noted that the girdle formed by the great current systems surrounding the Sargasso Sea prevents the entrance of any considerable quantity of colder water from higher latitudes.

To its great depth, freedom from islands and distance from the continents is to be ascribed the exceptional transparency of the water in the Sargasso Sea. The greater part of this region is between two and three miles in depth—altogether too deep therefore for any storm waves to stir the sediments lying at the bottom. And because of its distance from the coast, all sediments brought down by continental rivers are precipitated long before they can reach this region.

Another factor that makes for the great transparency of the water in this region and at the same time helps explain the deep blue color is the poverty of the Sargasso Sea in the minute plant and animal life that goes under the name of plankton. This term has come into use to describe the minute marine organisms that without volition are carried hither and thither by currents. It has been found in general that waters rich in plankton appear green, while waters poor in plankton appear blue. And oceanographic research has shown that the Sargasso Sea is poorer in plankton than is any other region in the North Atlantic Ocean.

What is the origin of the seaweed or gulfweed found in the Sargasso Sea? How does it come there? This has

been a matter of controversy from the very beginning. A plausible theory which received early acceptance was that it grew on submarine banks near the Azores and Bermuda, from which it was torn loose by the action of the waves and spread over the area by current and wind. The sounding lead, however, soon showed the depths in this region to be altogether too great for the existence of such banks. About the middle of the nineteenth century an American expedition made a survey of this region and found depths always exceeding two miles. This made the theory of submarine banks in the Sargasso Sea supporting a growth of gulfweed altogether untenable.

Following this, it was thought for many years—down to the present time, in fact—that the gulfweed came from the shores of the West Indies and the Bahamas. Under this theory the gulfweed was represented as being torn loose by wind and wave and coming within the sweep of the Gulf Stream which bore it along into the Sargasso Sea. Here it drifted for a year or more; and dying, sank beneath the waves, the place of this dying gulfweed being taken by a new crop brought in by the Gulf Stream from its place of birth.

It was known, however, that the gulfweed drifting in the Sargasso Sea was destitute of the ordinary organs of reproduction which are found on the gulfweed that grows attached along the coast. This raised the question whether the Sargasso Sea gulfweed is not a different species which is born, lives and dies in the open sea. This question is answered in the affirmative by the most competent authorities of the present day. According to the latest theory, therefore, the gulfweed in the Sargasso Sea is an adaptation of the plant to the open sea. It does not come from the coast but lives and propagates vegetatively or by partition year after year. Some replenishment from coastal plants is conceded, but such replenishment is regarded as

of very minor importance in the maintenance of the Sargasso Sea as a whole.

If the gulfweed within the Sargasso Sea originated in the shallow waters along the Bahamas and West Indies, it is reasonable to expect that some of the floating plants would be found with roots attached. But it is a curious fact that the gulfweed in the Sargasso Sea has no roots or other organs of attachment. It floats on the water supported by the small air sacks with which it is provided. This absence of roots is, therefore, another strong point in favor of the independent origin of the gulfweed in this particular region.

The gulfweed occurs most frequently and in greatest quantity within the central part of the Sargasso Sea. Farther out it occurs less and less frequently. Drifting patches may, under the action of wind and current, at one time be carried to places which at other times are free from gulfweed. Where, therefore, shall the limits of the Sargasso Sea be set? Obviously this is a matter of definition. If we define the Sargasso Sea to constitute the region over which gulfweed *may* be expected to occur, the limits will have to be drawn over a much larger area than if we define it to cover the region in which gulfweed occurs *frequently.* The latter definition is preferable, however, on a number of counts, and more especially because it accords better with the other characteristic features of the Sargasso Sea.

Defining the Sargasso Sea as the region in which gulfweed occurs frequently, it is found to delimit an area lying between the 20th and 40th parallels of north latitude and between the 35th and 75th meridians west of Greenwich, as shown by the dotted area in Figure 2. As defined above, the Sargasso Sea has a fairly regular oval outline with a hump northward of Bermuda. Withih the limits shown, it covers an area of approximately two and one half million

square miles—but little less than the area of all of continental United States.

How large a quantity of gulfweed is there in the Sargasso Sea? Occurring as it does in scattered patches over so large an area, it is obvious that to answer this question with any pretense at precision would require rather extensive observations. Captain Dixon found himself interested in the question and on several voyages he towed a net for a known distance and then weighed the resultant catch of gulfweed. On the basis of his observations he estimated

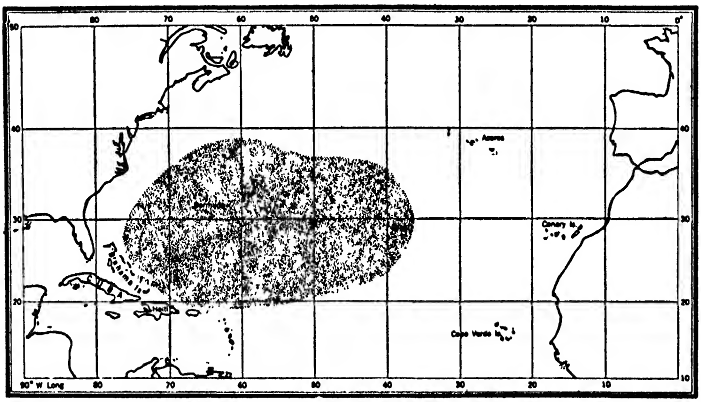

FIG. 2.—THE SARGASSO SEA

the floating gulfweed in the Sargasso Sea to aggregate twenty million tons.

Another question that naturally arises in this connection is whether the vegetation of the Sargasso Sea can be made commercially useful. The ashes of the gulfweed contain substances that are of importance in various industrial arts and suggestions for their commercial exploitation are made from time to time. It is, therefore, not wholly outside the bounds of probability that the Sargasso Sea may some day furnish the raw material of an active industry.

A varied and specially adapted animal life is found in the Sargasso Sea. This special adaptation may be taken to testify not only to the independent origin of the gulfweed here, but as testimony also to the great age of the Sargasso Sea. But, curiously enough, it has been discovered that this sea is singularly poor in bird life. To be sure, the greater part of this region is at a considerable distance from land; but in other regions of the North Atlantic which are just as far from land the frequency of birds is many times that in the Sargasso Sea. The explanation of the scarcity of birds here appears to be that the masses of drifting gulfweed afford a hiding place for the fishes and crabs that serve as food for birds, making capture more difficult than in areas free from gulfweed.

In recent years a further discovery has been made that marks the Sargasso Sea off from other regions of the open ocean. It has been found that the European eels, which occur in great numbers in the North Sea, in the Baltic and in the Mediterranean, have their breeding grounds within the warm and saline waters of the Sargasso Sea. Here, at the close of winter, the eels spawn. In the course of the following year the larvæ disappear from the spawning grounds, having moved into the central Atlantic region; and a year later they appear on the western shores of Europe and in the Mediterranean.

CHAPTER V

THE NORTHWEST PASSAGE

THE voyages of exploration of the fifteenth and sixteenth centuries, which culminated in the crossing of the ocean and which discovered America, found the sea route to the Indies, and circumnavigated the globe, were made under the auspices of two southwestern European nations, Spain and Portugal. Northwestern Europe did not take up the exploration of the sea till somewhat later, the stimulus coming from various sources. For the British, the desire to reach the Indies by a shorter route played a not inconsiderable rôle.

As an English writer of the sixteenth century put it, there were "foure famous wayes . . . to those fruitfull and wealthie Islands" of the Orient. The Portuguese were exploiting the southeastern route by way of the Cape of Good Hope. The Spaniards, through Magellan's voyage, had preëmpted the southwestern route. These routes were long; but for the English they were even longer than for the sailors from the more southerly ports of Spain and Portugal. For the English a northerly route would obviously be shorter. Was it not possible to reach the Pacific by sailing northeasterly from England and rounding the northern coast of Russia? Or better yet, could not the Indies be reached by sailing a little north of west and rounding the coast of America? Thus arose the quests for the Northeast and Northwest passages.

In the early years of the second half of the sixteenth century an English expedition started in search of the

Northeast Passage under the patronage of a merchant company. It sailed around the Scandinavian peninsula and reached the White Sea. A second expedition several years later reached farther northeast but was beset with ice. And it soon became apparent that this route was not practicable. Of the four possible routes to India the Northwest Passage was now the only one untried, and during the reign of Queen Elizabeth (1558-1603) a number of expeditions were sent out in the attempt at finding this route.

Of the northern regions in general, there was at this time but little definite information, and of the northwestern coasts of America there was no information whatever. Maps of these regions were therefore based on conjecture; but so soon as they appeared on a map they assumed an aspect of certainty altogether unwarranted by the vague conjectures on which they were based. When in the latter decades of the sixteenth century the idea of a northwest passage gained wide currency in England, it was possible to quote in favor of its existence and practicability the more important maps of that time.

In 1576 there appeared *A Discourse of a New Passage to Cataia*, written by Sir Humphrey Gilbert, in which the feasibility of a northwest passage to Cathay was advocated. As a result of considerable study of the question Gilbert concluded that North America was bounded on the north by a strait which led directly into the Pacific Ocean and in his *Discourse* he included a sketch map showing this strait. Gilbert put forward various arguments to prove the practicability of a northward passage to China, and in the concluding chapter urged the advantages that would accrue to England from this new highway of commerce to the wealth of the East.

Such was the interest in the question at the time that the appearance of the *Discourse* found preparations actually being made for an expedition in search of the Northwest

Passage. And two months after its publication, Martin Frobisher, with a fleet of three vessels and a crew of thirty-four men, set out to find the new route. It was a small fleet, consisting of two vessels each of twenty-five tons burden and one smaller vessel of ten tons. Leaving England in June of 1576, they encountered great storms after passing the Shetland Islands and lost the smaller vessel. In July they sighted land—probably the southern coast of Greenland—but ice prevented them from landing. Soon afterwards, the two vessels became separated and one, discouraged by the ice, turned homeward, arriving in London in September.

With his remaining vessel, Frobisher continued sailing westward, sighting the coast of Labrador toward the end of July. A few days later, he reached what is now known as Frobisher Bay and for the following three weeks the region in the vicinity was explored. On one of the islands five of Frobisher's men were enticed by an Eskimo and were never seen again. This left the ship with but thirteen men and boys. Frobisher therefore turned back toward England, London being reached October ninth.

This first voyage of Frobisher's in search of the Northwest Passage brought back favorable reports regarding the possibility of the passage. There was brought back, too, a piece of black stone picked up on one of the islands. Following the return of the expedition it was reported to contain gold and the next year a larger expedition was fitted out primarily for the purpose of bringing back a large quantity of the ore. This second expedition of Frobisher's consisted of three vessels—one of two hundred tons—and a complement of one hundred and twenty men. Leaving England the latter part of May, 1577, the expedition reached Frobisher Bay in July. By the middle of August they had collected nearly two hundred tons of ore and a week later they set sail for England.

The following year Frobisher led still another expedition; but this likewise was primarily for the purpose of bringing back ore which was still believed to be rich in gold. Fifteen vessels now constituted the expedition. This time stormy weather drove the fleet into Hudson Strait up which they sailed about sixty miles. But the primary object of the expedition being ore, this strait was not followed up further, and by the end of August, 1578, the fleet set sail toward England carrying more than a thousand tons of the so-called ore.

It was not long after this that the ore was found to be worthless and the intense interest aroused by the last two expeditions subsided. But the idea of the Northwest Passage did not die. In the summer of 1585 John Davis left England with two vessels. Sailing northwesterly, he entered Cumberland Sound, which he conceived to be the desired passage and spent ten days exploring it. Adverse winds now decided him to return to England, where he reported "the north-west passage is a matter nothing doubtfull, but at any tyme almost to be passed, the sea navigable, voyd of yse, the ayre tollerable, and the waters very depe."

In the following year Davis started from England in May with four vessels. This time, however, his progress in the northern waters was greatly impeded by icebergs and fogs. Several inlets south of Hudson Strait were explored, and then the expedition returned to England. The failure to reach China was disappointing to a number of the merchants who had subscribed to the venture; nevertheless, sufficient backing was secured to permit Davis to lead another expedition the following year. On this voyage Davis coasted the Baffin Bay shore of Greenland as far north as latitude 72°. Here the sea appeared open toward the west, and Davis thereupon sailed westward about forty miles, when he was stopped by wind and ice. He made

further explorations, however, to the southward along the western coast before he turned back toward England.

Davis still was of the opinion that the Northwest Passage was practicable, but no further expeditions for this purpose were sent out for fifteen years. In 1602 the East India Company sent out an expedition of two vessels under George Waymouth with the express purpose of finding a Northwest Passage. The fleet left in May, carrying a letter from Queen Elizabeth to the "great, mighty and Invincible Emperour of Cathaia." But early in September they were back again in England, having accomplished nothing more than the previous expeditions.

Of the half dozen or more expeditions which set out during the next thirty years in search of a Northwest Passage, it will be sufficient to mention those associated with the names of Hudson and Baffin. Henry Hudson's explorations are commemorated in the names of Hudson River, Hudson Bay, and Hudson Strait—all the result of voyages into northern waters in search of a shorter route to China. In 1607 he attempted to find a route across the polar sea; in the following year it was the Northeast Passage he set out to find, and in 1609 he attempted first a Northeast and then a Northwest Passage. It was in this latter attempt that he entered New York Harbor and sailed up the Hudson River.

In 1610 he set out again to find a Northwest Passage, of the existence of which he was firmly convinced. Sailing from London in April he entered, in June, the strait which now bears his name and a month and a half later Hudson Bay. The following three months were spent in exploring this body of water, and, winter setting in, the party went into winter quarters here. During the long winter, discontent broke out, culminating in mutiny the following June when the crew put Hudson, his son, and seven others

into a small boat and left them to their fate. Nothing more was heard of Hudson and his companions.

William Baffin had accompanied several expeditions into northern waters and came to the conclusion that if there were a Northwest Passage it was through Davis Strait. In 1616 he was sent out on a voyage to try this route. Passing through Davis Strait, Baffin entered the bay that now bears his name, and sailed as far north as latitude 77° 45′, a point not reached again for several centuries. A considerable extension of geographic knowledge of the northern regions resulted, but the problem of the Northwest Passage was no nearer solution. Indeed, the solution was no nearer as a result of several further expeditions in the decade and a half following Baffin. Whether or not such a passage existed was still an open question. And, even if there were such a passage, there was still the further question of its practicability.

With the third decade of the seventeenth century the first phase of the search for the Northwest Passage ends. For more than half a century now the problem had been attacked vigorously without any considerable advance in its solution. But, while the immediate object was still far from being attained, it would be an altogether false conclusion if the results of this quest were considered fruitless. Mankind had now acquired some real knowledge of land and sea in the northern regions; new and valuable fishing grounds were brought to light and exploited; and the necessary experience was gained which permitted the ultimate solution of the problem.

That this experience was necessary, even in such matters as the maintenance of health in Arctic regions, is illustrated by the fate of the Danish expedition under Jens Eriksen Munk, which set out to find the Northwest Passage in 1619. Captain Munk was an experienced navigator and had been to Iceland and also to the Russian Arctic regions. Leaving

Copenhagen in May, Munk took his two ships through Hudson Strait and, crossing Hudson Bay, decided to winter on its western shore. Alert to the need of proper food and exercise, Munk organized parties for hunting berries and fresh meat. But the dreaded scurvy soon appeared, and before the middle of December the first death had occurred. Out of a total of more than sixty men only Munk and three others were surviving by the following June, and these were in a greatly weakened condition. By this time it was possible to get some fresh fish and the survivors began to gain strength, and by the middle of July they left in the smaller of the two vessels, arriving home in September.

The period of quiescence that followed the first phase of the search for the Northwest Passage lasted for more than a century. It was only in 1741 that the matter received attention again, a British expedition setting out in that year to discover a passage through Hudson Bay. During this period of quiescence, however, progress made in another direction stimulated renewed interest in the Northwest Passage. The Russians were exploring the northern coast of Siberia, and about the middle of the seventeenth century they had discovered the strait separating Asia from America. These discoveries did not become known till much later, the strait itself being named after Vitus Bering, a Danish explorer in the Russian service, who sailed through it in 1728. But so soon as they became known it was but natural that they should revive interest in the Northwest Passage; for now that it was definitely proven that the sea separated Asia and America on the west, there was very much greater probability of the existence of such a passage. Further interest was aroused in 1745 by the offer on the part of the British Government of $50,000 for the discovery of the Northwest Passage, and thirty years later a further reward of $25,000 was offered to the ship reaching the latitude of 89° N.

The expedition of 1741 was no more successful than those of the previous century and the same comment is to be made with regard to several others following. In 1776 an attack on the problem was made from both the eastern and western entrances. In that year the famous navigator, James Cook, who during the eight years preceding had carried out two notable voyages of exploration, sailed from England for the Pacific with instructions to sail up the Pacific Ocean and endeavor to find the Northwest Passage from its western terminus. At the same time an expedition was sent to Baffin Bay to coöperate from the Atlantic Ocean entrance. Cook sailed through Bering Strait and reached latitude 70½° N. when he was stopped by the ice. He returned for the winter to the Hawaiian Islands and here he lost his life in an attack by the natives.

Another lapse of forty years followed now, due to American and European wars. Then in 1818, to stimulate anew the search for the Northwest Passage, the British Government offered a further reward of $25,000 for the crossing, in the Arctic regions, of the meridian of 110° W. And in that same year an expedition under Captain John Ross set out. No notable advance resulted from this expedition; but the following year Edward Parry, who had been second in command under Ross, led an expedition which entered hitherto unknown waters and advanced as far west as longtitude 114° W.

Leaving England in May of 1819, Parry sailed along the west coast of Greenland as far as 73° N. and then struck across Baffin Bay, though he found it dotted with icebergs. Lancaster Sound, north of Baffin Island, was entered in August and finding open water the expedition had the satisfaction of heading into undiscovered waterways. In September they passed longitude 110° W. and thus earned the reward offered the year before. Soon after this they were stopped by the ice and the party went into winter quarters

on the south coast of Melville Island. Parry's splendid leadership brought them through the winter in excellent condition, and when the ships got free from the ice in the following summer the explorers set sail for the west in the hope of attaining Bering Strait. Heavy and extensive fields of ice, however, prevented any considerable westward advance, 114° longitude being the most westerly point attained. Finding that nothing more could be done, Parry turned homeward, the expedition reaching England in November, 1820.

A glance at a map of the north polar regions will show the very considerable advance made by Parry. The most westerly point reached by him, longitude 114° W., is more than half the way from Greenland to Bering Strait. There could now be scarcely any question as to the existence of a passage between the Atlantic and Pacific oceans. To this expedition of Parry's is to be credited also the discovery of a number of islands in the regions traversed. Furthermore, in an expedition which spent considerably more than a year in the Arctic, good health had been maintained, only one death occurring, and that from a non-Arctic cause.

On their return to England the party was hailed with great enthusiasm, and preparations were immediately made for a second expedition under Parry's leadership. In May of 1821 Parry left for the Arctic again. This time he decided to strike westward in lower latitudes, and he therefore entered Hudson Strait, and sailed into Fox Basin. Until winter set in he examined various inlets for an opening westward out of Fox Basin without success. The winter of 1821-22 was spent on an island, and the following July they resumed their search and discovered a way out. This was only partly free from ice and not much progress had been made when winter again set in. It was not until August of 1823 that they could leave their winter quarters, and, progress westward appearing impossible, the expedi-

tion returned to England. While geographical discoveries had been made and scientific data of various kinds gathered, the results, so far as the Northwest Passage was concerned, were negative.

In 1824 Parry made a third attempt. Ice conditions this year were unfavorable. After spending the winter in the Arctic, one of the two vessels had to be abandoned, and the expedition returned to England in the fall of 1825. Four years later an expedition under Captain John Ross made another attempt. While unsuccessful in advancing the quest for the Northwest Passage, this expedition is of interest in a number of respects. In the first place it marks the first use of a steam-driven vessel in Arctic exploration. The engine, however, was not well made and proved useless. In the second place this expedition spent four years continuously in the Arctic. Their vessel had become frozen in the first winter and finding it impossible to get her clear of the ice, they abandoned her, the return to England being made in a whaling ship which they were fortunate enough to encounter. It was during this expedition, too, that the position of the north magnetic pole was determined.

In the two decades between 1820 and 1840 there occurred a considerable extension in the knowledge of the Arctic coast of America. This resulted mainly from the work of land explorers. From Bering Strait eastward to longitude 95° W., a distance of approximately 1,500 miles, the coast was now known. Parry, it will be recalled, had in higher latitudes penetrated from the Atlantic Ocean as far as longitude 114° W. To discover the Northwest Passage there remained therefore but a relatively small territory to be explored. And it was for this purpose that in 1845 an expedition was organized under Sir John Franklin.

With two vessels and 129 men, the expedition left England in May of 1845 and in the latter part of July they were seen by a whaler in Baffin Bay. Subsequent move-

ments must in part be conjectured, for the only information from the expedition itself is contained in a note, the last date of which is April 25, 1848, that was found by a search party later. This note stated that the ships had been left three days earlier near King William Island, having been icebound since September, 1846. It also told of the death of Sir John Franklin and of the intention of the party to start, on foot, for Back River on the Canadian coast. But this was a forlorn hope; for in a desolate land, with failing provisions, their fate was sealed. Search parties later found the route marked by graves and skeletons. Three years before they had set out determined to tear the veil that still shrouded that part of the Arctic; and, as if in warning against further encroachment on a domain thus far successfully defended against the dominion of man, the Arctic exacted the supreme sacrifice from each one of that band of 129 dauntless men.

Franklin sailed through Lancaster Sound and Barrow Strait until stopped by the ice. He then turned north and sailed around Cornwallis Island and wintered on one of the islands to the south. From here his course is based on conjecture. But apparently, as soon as the ice permitted, a southerly course was steered to a point off King William Island where the winter of 1846-47 was spent. The Northwest Passage was now almost discovered, for the expedition was less than one hundred miles from the known shore of Arctic America.

It is quite possible that Franklin died happy in the knowledge that his expedition had discovered the Northwest Passage. Four journeys of exploration were made by traveling parties from the vessels during the period that they were icebound. And one of these parties may well have gone sufficiently far south to make sure of the existence of a continuous waterway leading north of the American coast. The Franklin expedition is generally

credited with the first discovery of the Northwest Passage; for on their final journey toward the Canadian coast they had covered the last stretch of the passage. To quote from a tribute to their memory, they "forged the last link of the North-West Passage with their lives."

Franklin's party had been provisioned for three years. When 1848 came round with no word from the explorers, anxiety was aroused and relief expeditions were sent out that year. Nothing was learned of the fate of the explorers that year or the following year, and in 1850 no less than twelve vessels were sent out in search of Franklin's party. Some of these went into the Arctic from the Atlantic and some from the Pacific. And it was one of the latter that succeeded in bringing back knowledge of the existence of a Northwest Passage.

Captain Robert M'Clure, commanding the *Investigator,* left England in January of 1850, passed through the Strait of Magellan and at the end of July reached Bering Strait. Entering the Arctic Ocean, M'Clure sailed his ship eastward more than a thousand miles before becoming beset by the ice, in the middle of September. He had by that time reached the strait between Banks Island and Victoria Island. In October, with a sledge party, he followed this strait to its northern end where it enters Melville Sound. Here Parry had come in 1819 from the east, and the existence of a Northwest Passage was now definitely proven—very nearly three hundred years from the time Martin Frobisher first set out in its quest.

It was fortunate for M'Clure that other search parties were active at that time. Three winters were spent in the Arctic. The winter of 1852-53 found the party in a precarious condition. It was necessary to abandon the icebound ship and plans were being made for retreat which might well have ended as did that of Franklin's party. Early in April of 1853, about ten days before the retreat

was to have begun, a sledge-party from an expedition wintering to the eastward appeared. M'Clure and his party joined the latter expedition, returning to England by way of Lancaster Sound. They were, therefore, the first to make the Northwest Passage, although part of it was made in a sledge, and they received the reward of $50,000 offered for that achievement.

Subsequent explorations have developed more fully the geography of the Arctic Archipelago. And, as a glance at a map of the region shows, there are, in truth, a number of Northwest Passages. But it was not till after the beginning of the present century that a ship actually made a Northwest Passage by sailing from one ocean into the other. In 1903 Roald Amundsen and six other descendants of the Vikings left Norway in the *Gjoa*, a small sailing ship fitted with an auxiliary engine. The expedition was very carefully planned. It followed approximately the route of the Franklin expedition and, after emerging into the Arctic Ocean, the *Gjoa* sailed along the northern coast of America, finally passing through Bering Strait into the Pacific. Norway was left in the middle of June, 1903, and Nome, Alaska, was reached by the end of August, 1906, three winters having been passed in the Arctic.

Nothing like as much time and effort was spent in the search for the Northeast Passage. Early in the second half of the sixteenth century several expeditions under the auspices of English merchant companies were sent out in an attempt to reach India by way of the Northeast Passage. Finding it impracticable, little further effort was made in that direction. The Russians, however, in various expeditions brought to light the whole of the Arctic coast of Asia, Bering Strait being discovered by a Russian party about the middle of the seventeenth century.

As a result of the Russian explorations the existence of the Northeast Passage was known long before the continuity

of the Northwest Passage was demonstrated. And this passage was made in a single voyage about a quarter of a century before Amundsen made the Northwest Passage. In July of 1878, Baron Nordenskiöld sailed from Sweden in the steam whaler *Vega*. Steaming along the Siberian coast, Cape Chelyuskin, the northernmost point of Asia, was rounded in August. East of this point ice made the going slower; still progress was possible till the latter part of September. By this time only a little over a hundred miles remained between the *Vega* and Bering Strait. For very nearly ten months the vessel was icebound, getting free only in the middle of July of the following year, Bering Strait being passed several days later.

CHAPTER VI

THE ATTAINMENT OF THE POLES

SOME vague knowledge of the northern regions must have reached the Mediterranean world at an early date; for in the Homeric poems we find references to the long days of summer and the long nights of winter in the north. In the fifth century before the beginning of the Christian era we come across further evidence of such vague knowledge in the conception of geographic zones, the outermost two of which were uninhabitable because of extreme cold. In the fourth century, however, authentic information was brought back by the Greek explorer, Pytheas.

As noted in the first chapter, all of Pytheas' writings have been lost, and our knowledge of his journeys is based on casual mention by later writers. From these writers it appears that Pytheas told of an island which he called Thule, lying six days' sail to the north of Britain where the nights at times are but of two or three hours' duration. And beyond Thule, Pytheas related, the sea became of a thick and sluggish nature, like neither land nor sea, which "can neither be traversed on foot nor by boat."

No further voyage into the northern regions by the ancients is known. What the civilized world thought of these regions about the first century A.D. may be gathered from Pliny's statements in his *Historia Naturalis*. "This part of the world is accursed by nature and shrouded in thick darkness; it produces nothing else but frost and is the chilly hiding-place of the north wind."

There are reasons for believing that during the early

Middle Ages—about the eighth century—Irish monks had discovered the Faroe Islands and Iceland. The Norsemen, as we have seen (Chapter II), colonized Iceland toward the close of the ninth century and Greenland somewhat later. But as far as western Europe is concerned, definite knowledge of the northern regions dates from the beginning of the quest for the Northeast and Northwest passages. In the search for these, expeditions were relatively frequent and soon a considerable store of knowledge regarding the north polar regions resulted.

In the search for the Northwest Passage the English took the leading part, the principal voyages being discussed in the preceding chapter. In the search for the Northeast Passage mention must be made of the explorations undertaken by the Dutch. Beginning in 1594, and continuing for three successive years, Dutch expeditions sailed into the Arctic in the hope of finding a Northeast Passage. Willem Barents took part in all three expeditions, and on the last one Spitzbergen was discovered. It was during this voyage, too, that a winter in the Arctic was first successfully passed, although Barents himself died before the return of the expedition to Holland.

The explorers in search of the Northeast and Northwest passages brought back news of the wealth in fishes of the Arctic and as early as the first decade of the seventeenth century the whale fishery in the region about Spitzbergen was begun by English seamen. They were followed by the Dutch, and later, when Davis Strait proved a valuable fishing ground, it was likewise exploited by the Dutch and the English. These whalers added considerably to the knowledge of the regions they traversed in pursuit of whales. It was an English whaler, Captain William Scoresby, who, in 1820, published the *Account of the Arctic Regions,* which became the standard work on the subject. This same Scoresby was with his father on board

the *Resolution,* a sailing ship of about 300 tons, while engaged in whaling around Spitzbergen in 1806. Determined to see how far north it was possible to reach in a ship, the elder Scoresby entered the ice in latitude 76° N. and two months later by expert seamanship reached latitude 81° 30′. This was the farthest north attained at that time.

By the middle of the nineteenth century the Northwest Passage had been discovered, and this removed from the field of Arctic exploration a problem that spurred the efforts of explorers for several centuries. To be sure there were still vast stretches in the north polar regions that were wholly unknown, standing challenges to the explorer. But these lacked the dramatic appeal that lay in the search of a Northwest Passage. There was still left, however, the attainment of the North Pole, a prize sufficiently alluring to capture the imagination.

Even before definite knowledge of the Arctic regions had been acquired, attempts at reaching the Pole had been made. But in the third decade of the nineteenth century we find an experienced Arctic explorer making the attempt. In 1827, Edward Parry, whose voyages in search of the Northwest Passage between the years 1819 and 1825 were discussed in the previous chapter, led a carefully planned expedition bent on reaching the North Pole.

Parry's idea was to use Spitzbergen as a base and from there to make the attempt in two specially constructed boats which were fitted with steel runners so that they might be used as sledges on the ice. In May of 1827 the expedition left England, Spitzbergen being reached by the middle of June. On the twenty-first of that month the two boats, with fourteen men in each and with provisions for seventy-one days, set out for the Pole. After two days the ice made it necessary to haul the boats up and use them as sledges. Progress was extremely slow; fog and rain were frequent, as were also pools of water on the ice floes

over which they trudged. They discovered, too, that the ice was now moving south at a rate which very nearly equaled their travel over it to the north. For more than a month now they had been traveling over the ice and had attained latitude 82° 45′ N. Turning back they reached their ship at Spitzbergen on the twenty-first of August after an absence of sixty-one days.

Of the numerous expeditions into the Arctic it will be possible here to notice only the outstanding ones. Parry's highest latitude, 82° 45′ N. remained "farthest north" for nearly half a century. It was not till 1876 that it was passed. In that year A. H. Markham of the British expedition under the command of Captain George Nares reached latitude 83° 20′ N. Six years later J. B. Lockwood, of the American scientific expedition under command of Lieutenant A. W. Greely, reached 83° 24′.

Greely's party was one of a number of scientific expeditions that went into the Arctic in 1882. These had their origin in the efforts of the Arctic explorer, Lieutenant Charles Weyprecht of the Austrian navy. Stressing the importance of scientific investigations in the Arctic, he urged international coöperation; more specifically, he suggested the establishment of a number of stations within the Arctic at which simultaneous observations would be secured. He did not live to see his suggestions carried into effect, but they bore fruit in a plan entered into by ten countries under which a dozen expeditions were sent into the Arctic, the plan contemplating a full year of observations beginning in August, 1882.

Lieutenant (later Major-General) Greely of the United States Army was in charge of the expedition that was to make the observations at Lady Franklin Bay. The party consisted of twenty-five men. In August of 1881 they were landed at their station with provisions for two years. Quarters were speedily built and scientific observations

commenced. Two winters were passed without accident, and it was during the first winter that Lockwood made the sledge journey that passed Markham's farthest north of 1876. A relief ship had been expected in 1882 but neither that year nor the following year did it show up and in August of 1883 Greely led his party toward Smith Sound. Here they were forced to winter on short rations, the last ration being issued on May 24. The only food remaining was sealskin thongs. One by one, members of the party died of slow starvation. One member of the party who had repeatedly stolen food was ordered shot. Greely and five others were found, but in greatly weakened condition, by a relief ship on the twenty-second of June, 1884. All scientific records and collections, however, were intact.

In 1893 the Norwegian explorer Fridtjof Nansen inaugurated a new era in Arctic exploration by a novel and daring plan. In studying the oceanography of the Arctic Ocean he came to the conclusion that there was a general westward drift of the ice across the polar basin. Might not a ship frozen in the ice pack near the New Siberian Islands drift across or near the Pole? Nansen resolved to attempt this, and planned the expedition with great foresight. The vessel made use of, the *Fram*, was specially built, of great strength to resist the crushing effect of the ice and with sides so designed that when caught between ice masses the pressure would tend to lift her out. The party altogether totaled thirteen—apparently Nansen was free from superstition.

In July of 1893 the *Fram* sailed from Norway, and by the end of September the vessel was frozen into the pack ice near the New Siberian Islands. In the twelve months following, the *Fram* drifted nearly two hundred miles in a northerly direction. And in the second winter Nansen decided to leave the ship and with one companion to make an attempt at reaching the Pole with dog sledges. It was

an extremely daring undertaking, for it was obviously out of question to attempt a return to the drifting ship. Nansen's plan was to make instead for Spitzbergen where he hoped to fall in with some tourist steamer, the *Fram* meanwhile continuing her drift.

Leaving the ship in March of 1895 Nansen and Hjalmar Johansen continued northward for twenty-six days when latitude 86° 28′ was reached. But by this time it was imperative to turn back—one of the islands of Franz Josef Land being reached in August. Here under great hardships they wintered until May of 1896. They then resumed their journey and on the fifteenth of June near Cape Flora they met an English Arctic exploring party in whose vessel they returned to Norway. The *Fram* had meanwhile continued her drift and after more than a thousand days in the ice, the ship reached Norway, only a few days after Nansen.

A year after Nansen's safe return another Scandinavian made an equally daring attempt to cross the Pole. By means of a specially constructed balloon the Swedish aëronaut, S. A. Andrée, proposed to fly northward from Spitzbergen. On the afternoon of July 11, 1897, Andrée and two companions ascended in the balloon. After this, the only news received of the expedition is contained in three message-buoys which were found, all dropped on the eleventh. The last one was dated 10 P.M. and reported that the balloon was in latitude 82° N., longitude 25° E. and that all were well.

Nansen's farthest north was passed in 1901 by Captain Umberto Cagni of the Italian navy, who was second in command of the expedition under the Duke of the Abruzzi. The base of operations of this party was established in Franz Josef Land and in March of 1901 Cagni started with ten men and ninety-eight dogs. His plan was to send back one detachment in twenty-four days and a second

detachment after forty-eight days. This would permit him to start with full supplies from that point and continue the advance for seventy-two days. The going proved slow during the first ten days, the average being eight miles. On the eleventh day it was found advisable to send back three men—these were never seen again. The second detachment was sent back nine days later and reached base in safety. Cagni with three companions now continued the advance until April 25th when latitude 86° 34′ N. was reached. Here he found it necessary to turn back, the return journey covering sixty days.

It was not till the twentieth century that latitude 90° N. was attained. In 1909 the American explorer, Robert Peary, after very nearly a lifetime spent in single-minded devotion to that end, achieved the Pole. Peary began his Arctic exploration in 1886 on the west coast of Greenland. Again in 1891 and in 1893 he returned to Greenland, and during each of these expeditions carried out notable exploratory work. In 1898 he returned to the Arctic and spent four years there. During the first winter of this expedition his feet were badly frozen, necessitating the amputation of eight toes, but in a few weeks he was back in the field. And toward the end of the expedition he set out northward for the Pole, but was compelled to turn back after reaching 84° 17′ N.

In 1905 Peary led another expedition, and in the course of this he was successful in reaching 87° 6′, which was the nearest approach to the North Pole up to that time. In 1908 he started out on the voyage that was to crown the efforts of more than twenty years. Leaving New York on the *Roosevelt* in July of 1908, the expedition reached Cape Sheridan on the northeastern coast of Grant Land in September. The base of operations was then established at Cape Columbia, nearly a hundred miles northwestward, and from here Peary set out for the Pole on the first of

March, 1909. As the party progressed northward, different sections returned, leaving the best dogs and extra supplies with the leader. At 87° 48′ the last supporting party turned back. From here Peary with his negro servant, four Eskimos and forty dogs set out for the final dash; latitude 90° N. being reached on April 6. The North Pole was attained.

In the cursory recital here of the steps in the attainment of the North Pole, there is scarcely a hint of the dramatic story of Man's conquest of the frozen waste. Some day a master will tell this epic of the north. In its proper setting he will tell of the changeless life of this region through unnumbered ages, ruled by the grim northern gods. Here and there over their vast demesne, these gods suffered the presence of a small tribe or two of the beings that had risen to power in the lands to the south. But these were not lordly here—they had made their peace and eked out a miserable existence, content to be the playthings of fate. He will tell how, at rare intervals, some intruder from the south ventured into this forbidding domain and returned, awed by its grim prospect. An inquisitive Greek bringing back tales of a region that was neither land nor water, some daring Viking sailing his cockleshell into the face of danger—only these disturbed the slow rhythm of life in this ancient system.

And then he will tell of a day when the gods of the north were holding high carnival. Turning their gaze downward for a moment they beheld in amazement a frail craft or two within their domain, manned by the fair-skinned strangers from the south. How they roared with laughter when they divined that these puny beings were challenging their dominion! With grim mirth they watched as the ships were crushed by the ice, as the crews were decimated by disease and starvation.

But what strange beings were these? Undeterred by

hardship, by death itself, these men from the south fling their challenge at the gods again and again. With each passing year they reach farther and farther into the forbidden land. And more disturbing still, they are learning ways of conquering the north, learning to make themselves at home here. Now a determined leader at the head of six score men and more is making another sally into the Arctic. Surely it is time to halt this advance and strike a telling blow—not a single one of these shall be spared! And the wrath of the gods descends on Franklin and his men.

The gods now breathe freely again, their dominion is secure. But what is this? From the tracks of the stricken men rises a larger army to complete the task. These must be possessed of an immortal spirit, and fear grips the hearts of the gods. But doggedly they fight the northward advance of Man, yielding ground only slowly, and when the final assault is made, the land is dotted with the stricken bodies of many valiant explorers.

And all the while the gods are puzzled, "What brings Man here?" they keep asking. "Are not safety and comfort the ultimate good he strives for?" In his epic of the north the master will answer the gods. Into this answer he will weave the varied motives that have led men from all walks of life into the Arctic. For the present we may quote the words of the Norseman who sought to answer this question simply, some six hundred years ago:

> If you wish to know what men seek in this land, or why men journey thither in so great danger of their lives, then it is the threefold nature of man which draws him thither. One part of him is emulation and desire of fame, for it is man's nature to go where there is likelihood of great danger, and to make himself famous thereby. Another part is the desire of knowledge, for it is man's nature to wish to know and see those parts of which he has heard, and to find out whether they are as it was told him

or not. The third part is the desire of gain, seeing that men seek after riches in every place where they learn that profit is to be had, even though there be great danger in it.[1]

Into his epic the master will weave tales of astounding feats of courage and devotion, of the blazing forth of the human spirit under privations of the most trying kinds, of torturing death met calmly. He will tell how even those who, nurtured under conditions that early stifled the development of the finer flowers of the human spirit, met the challenge of the north with dignity and asserted the triumph of the spirit. For contrast, too, he will find some who under the terrible conditions forgot their manhood, but these will be rare. For of the many pages that constitute the Book of the North only few are sullied by dishonor.

The region surrounding the South Pole did not engage the attention of the explorer as early as did the north polar regions. Being much closer to the centers of maritime activity, the latter naturally came within the knowledge of civilized mankind at an earlier date. Furthermore, the search for the Northeast and Northwest passages focused attention on the Arctic and acted as a powerful stimulus to explorations here, a stimulus which was wholly lacking in the Antarctic.

Down to the last decade of the fifteenth century, virtually nothing was known of the distribution of land and sea in the higher latitudes of the southern hemisphere. But, for one reason or another, there had come down from ancient times the belief in the existence of a large southern continent. When, in 1497, Vasco da Gama doubled the Cape of Good Hope, it served but to delimit the northern extension of the southern continent in that direction. Sev-

[1] Quoted by Fridtjof Nansen, *In Northern Mists,* Vol. I, p. 3.

eral decades later, when Magellan proved the insularity of America, the southern continent was still conceived as a great land mass extending into relatively low latitudes.

In passing through the strait which now bears his name, Magellan saw to the south the barren shores of Tierra del Fuego. This he thought part of the southern continent; and later explorers coming upon land here and there in this hemisphere likewise took for granted that it constituted part of the great continent surrounding the South Pole. In this connection it is to be recalled that not until the invention of the chronometer in the eighteenth century was it possible to determine longitude at sea with any degree of accuracy. As a result, the same land would be reported by different navigators at different places. The effect of this was to dot the southern hemisphere with reported discoveries of land which but confirmed the prevailing opinion of the existence of a large south polar land mass.

It was not until the latter half of the eighteenth century that the southern continent was shorn of a large part of its conjectural northward extension. In 1772 the great English navigator, Captain James Cook, left England on an exploring expedition into the southern hemisphere, during which he completely circumnavigated the earth in high latitudes. In the course of this the Antarctic circle was crossed for the first time—in January, 1773—and in January of the following year he reached as high as 71° 10′ S., farther southward advance being stopped by a compact ice field.

In a later chapter we shall have to consider the reasons for the great differences between the Arctic and Antarctic. Here it is important to note merely the difference as regards navigability. If we glance at a map showing the limits of pack ice in the northern and southern hemispheres, we find that in the former this limit lies almost wholly

within the Arctic circle, while in the latter it extends considerably outside the Antarctic circle. The latitude of 71° 10′ S., attained by Cook, was, therefore, to stand as the highest south for a number of years.

The detailed story of the exploration of the Antarctic cannot be told here. Various expeditions followed that of Cook. A notable one was the expedition sent out by the Russian government under Captain Bellingshausen which, between the years 1819 and 1821, duplicated Cook's circumnavigation of the earth in high southern latitudes, but Bellingshausen's farthest south did not exceed that attained by Cook in the previous century. In 1823, however, the British mariner, James Weddell, while engaged in sealing, reached latitude 74° 15′ S.

Another notable Antarctic expedition was that commanded by Sir James Ross which sailed from England in 1839. Ross had had a number of years' experience in Arctic exploration, and his two ships were very stoutly built. Therefore, when he reached the Antarctic ice pack, he plunged in boldly and during this expedition reached latitude 78° 5′ S. During its three-and-a-half-year cruise the famous *Challenger* expedition, which did so much to lay secure foundations for the science of the sea, crossed the Antarctic circle in 1874, being the first steamship to do so.

In 1900 an English expedition under command of Carstens Borchgrevink was able to take its ship as far as latitude 78° 34′ S. Landing on the ice, Borchgrevink advanced with dog sledges to latitude 78° 50′ S. In 1902 the British naval officer, Captain R. F. Scott commanding the *Discovery* expedition, reached 82° 17′ S., and in 1909 Lieutenant Ernest Shackleton with three companions pushed farthest south more than four hundred miles closer to the Pole, attaining latitude 88° 23′ S.

Shackleton's expedition is of interest in a number of

respects. He had been with Scott at the time the latter reached farthest south in 1902; and of the three making that journey he was the only one to break down. Notwithstanding this we now find him leading an expedition with the South Pole as objective. He took along eight Manchurian ponies intending to use them instead of dogs. Four, however, died during the first month in the Antarctic. The little whaler, *Nimrod*, had landed the party at Cape Royds in February, 1908, and after laying out depôts in advance Shackleton and three companions started for the Pole on October 29, 1908, taking the four ponies and sledges.

The ponies made rapid progress and on the twenty-first of November the eighty-first parallel was passed. At this time one of the ponies broke down and had to be shot, the meat being stored in a depôt for use on the return journey. A week later it was necessary to shoot another pony and on December first, the third pony. Six days later as they were toiling up a glacier the last pony fell into a crevasse. They had intended shooting the pony that night since the ice conditions were such that it could do very little. But they had planned to use it as food and its loss in that regard was serious.

Now it was necessary to pull the loaded sledges by hand. They were still climbing up the glacier with its dangerous crevasses into which one or the other of them was continually falling, only the sledge harness saving them. By the ninth of January, 1909, they had reached an elevation of more than 12,000 feet above sea level and on this day they attained their farthest south—only a little more than a hundred miles from their goal.

Seven hundred miles lay between them and the ship and this distance was covered in fifty-one days. An inadequate food supply sapped their strength; dysentery and snow blindness attacked them, the latter adding not only to dis-

comfort but making the finding of their food depôts more difficult—and on the sure finding of these depended their lives. Despite all this the exhausted men did not lighten their load of geological specimens which they were bringing back, and on March first they reached their ship.

In 1911 the South Pole was attained by Roald Amundsen, who already had to his credit the Northwest Passage. Setting out in the fall of 1910 he established a base on the Antarctic ice barrier in Ross Sea, latitude 78° S. Food depôts were laid down as far as latitude 82° S. and on October 20, 1911, together with four companions and fifty-two dogs, he started from his base for the Pole. The men traveled on skis, the dogs being used to pull four sledges stored with supplies. On the fifth of November they reached their depôt in latitude 82° and on the seventeenth they were in latitude 85°, where they established their main depôt, taking along with them supplies for sixty days. On December second they passed Shackleton's farthest south and on the fourteenth they were at latitude 90° S. Two days later they began the return journey, the base being safely reached on January 25, 1912.

Was the South Pole to be conquered without exacting the price of human life? Only a short time after Amundsen had nailed the standard of human achievement at the southernmost point of the globe, this price was paid. When Amundsen started for the Antarctic in 1910, Captain R. F. Scott was completing arrangements for an expedition he was to lead in an attempt at reaching the South Pole. Scott established his base on Ross Island, some four hundred miles to the east of Amundsen's base, and in October of 1911 his party began the journey to the Pole. Ponies and dog teams were used as far as 83° 30′ S. but from this point the sledges were hauled by hand. Supporting parties were detached at 85° 7′ and at 86° 56′, the polar party now consisting of Scott, Wilson, Bowers, Oates and Evans.

Scott and his companions knew that Amundsen, from his camp several hundred miles westward, was also bent on attaining the Pole. But it was an undertaking of the most difficult kind and the prize might yet be theirs. When, therefore, they reached the Pole on January 18, 1912, they were not completely taken by surprise to find Amundsen's tent and records which he left just one month previously.

To have reached the Pole only to find the prize already won was naturally disappointing. The homeward journey was, therefore, begun under disheartening conditions. On the sixteenth of February Evans collapsed, dying on the seventeenth. The weather proved unusually severe, and early in March Oates found himself with seriously frost-bitten feet. By the middle of the month he was at the end of his strength and rather than endanger the rest of the party by slowing their progress he resolved to sacrifice himself. Telling his companions that he was "just going outside and may be some time," he walked out into the blizzard that was raging.

March twenty-first found the three remaining explorers at the end of their strength with a furious gale blowing, and without fuel. Pitching their tent they lay down. And here their frozen bodies were found eight months later by a search party, with notebooks in order and with the geological specimens intact.

CHAPTER VII

THE EXTENT OF THE OCEANS

THE gradual unfolding of the true extent of the sea before Man's inquisitive gaze was very briefly sketched in the preceding chapters. For countless ages he had been but a passive instrument of nature. His utmost efforts were of little avail against the barrier of the sea and the overwhelming forces encompassing him; so that all his life he had been compelled to spend within the confines of limited parts of the earth. And for long it must have been questionable whether his feeble strength would ever suffice to release him from the cramping environment of a restricted locality.

To his mind—slowly developing through the ages—Man owes the power that made it possible to forge the instruments of his release. Coupled to his insatiable curiosity and his unbounded courage it has made him master of the whole world, enabling him to bestride it from east to west and from Pole to Pole. The mists that have shrouded the earth have been dispelled even at its uttermost ends; and while many spots still await more detailed exploration, in its larger features the distribution of land and sea may be considered as well known.

A knowledge of the true extent of the sea could come only at a relatively late date in the history of mankind. For not even a rough estimate was possible until two difficult problems were solved, namely, the area of the earth as a whole and the area of the land masses projecting above the level of the sea. This does not mean that it was

necessary to wait until data of great accuracy were at hand. But so long as the approximate area of the earth was in question, and so long as it was not known whether large parts of the earth's surface are occupied by land or water, just so long was it impossible to arrive even at an approximate figure for the extent of the sea.

Taking the earth as a sphere, the determination of its area is, in principle, very simple. For the area of a sphere is exactly four times that of a circle that has the same circumference as the sphere. And to determine the circumference of the earth it is only necessary to know the latitudes of any two places that lie on the same meridian and the distance between them. It will be recalled that as early as the third century B.C. Eratosthenes had arrived at a fairly correct figure for the circumference of the earth. But because of the crude methods in use for determining latitude and longitude, later geographers accepted a much smaller world. It was this world of considerably reduced dimensions that Columbus used in figuring the distance between Europe and India.

The great explorations of the fifteenth and sixteenth centuries did much to bring about a more correct idea of the size of the earth. Later came the development of the mathematical theory of the figure of the earth and of instruments of precision which permitted accurate geodetic measurements. As a result we now know the area of the earth to be, in round numbers, 197 million square miles.

Of the total area of the earth how large a part does the sea comprise? This question proved more difficult of solution than that relating to the size of the earth. For not until the surface of the earth had been explored in all its parts, was it possible to determine how much is sea and how much, land. As to the relative proportions of land and sea the ancients could hazard only the vaguest conjectures. But apparently the view that the land formed the larger

part was the prevalent view. Thus a passage in the Book of Esdras reads: "Upon the third day Thou didst command that the waters should be gathered in the seventh part of the earth, six parts hast Thou dried up and kept them."

The preponderance of the land was generally accepted in the Middle Ages. Not only was this view in conformity with the passage in Esdras quoted above, but from general considerations it could be argued that since God created the earth for man's habitation was it not reasonable to assume that He would make the greater part of it land? After the great explorations had shown the wide extent of the oceans, that view was no longer tenable; and it was then thought that land and sea were of equal extent—this view appearing in publications dating as late as the middle of the seventeenth century.

In the eighteenth century the development of instruments for determining position at sea with some degree of precision made possible the construction of maps which delineated correctly the position and extent of the various land masses. And this in turn made it possible to determine correctly the relation of land to sea. A modern globe represents, in miniature, this relationship and shows that the sea is a single sheet of water, the surface of which is broken by island land masses of various shapes and sizes. Certain areas in the north and the south polar regions are still unexplored and the proportions of land to sea there are still conjectural. But these areas are relatively small, and whatever the distribution of land and water there, it will not affect appreciably the relative proportion of land to sea over the earth as a whole. Of the total area of the earth the latest figures assign 139½ million square miles to the sea and 57½ million square miles to the land. On a percentage basis this means that 71 per cent of the earth's surface is sea and 29 per cent land. The sea therefore

covers an area about two and one-half times as great as the land.

The land masses that break the continuity of the sea are of varied size and of irregular shape. As a result the relative areas of land and sea vary in different latitudes. In 1921 Dr. Erwin Kossinna, a German oceanographer, published a table giving the areas of land and sea in each

DISTRIBUTION OF LAND AND SEA

ZONE	NORTHERN HEMISPHERE				SOUTHERN HEMISPHERE			
	Land (million sq. miles)	Sea (million sq. miles)	Land (per cent)	Sea (per cent)	Land (million sq. miles)	Sea (million sq. miles)	Land (per cent)	Sea (per cent)
0-10°	3.9	13.1	23	77	4.0	13.0	24	76
10-20°	4.3	12.2	26	74	3.6	12.9	22	78
20-30°	5.8	9.7	38	62	3.6	11.9	23	77
30-40°	6.0	8.0	43	57	1.6	12.5	11	89
40-50°	6.4	5.8	52	48	0.4	11.8	3	97
50-60°	5.7	4.2	57	43	0.1	9.8	1	99
60-70°	5.2	2.2	71	29	0.7	6.6	10	90
70-80°	1.3	3.1	29	71	3.3	1.2	73	27
80-90°	0.2	1.4	10	90	1.5	——	100	—
TOTAL ..	38.8	59.7	39	61	18.8	79.7	19	81

five-degree zone in both hemispheres. This is the latest calculation to date, and his figures have therefore been used in computing the values given in the table above. For our purpose it will be sufficient to take the areas in the different zones to the nearest tenth of a million square miles, that is, to the nearest hundred thousand square miles. It will be sufficient, too, to give the distribution of land and sea for each ten-degree zone.

Our knowledge of the geography of the regions in the high latitudes of both hemispheres is still far from com-

plete. It is, therefore, quite probable that as a result of future exploration, the figures given for the distribution of land and sea in several of the ten-degree zones in the high latitudes may be changed somewhat. It is equally certain, however, that such changes will be relatively small and that the picture presented by the table may be taken as giving with sufficient accuracy the larger features in the distribution of land and sea.

A glance down the columns giving the percentage distribution of land and sea shows immediately how greatly this distribution varies. It is of interest to note that the largest difference is between the two outermost zones. In the northern hemisphere this is almost wholly sea, while in the southern hemisphere it is wholly land. Of the 18 zones in the table, the sea dominates in 13 and only in 5 does the land cover a larger area. Of these 5 zones 3 are in the northern hemisphere and 2 are in the southern hemisphere.

Comparing the two hemispheres, it is seen that the sea constitutes the dominant feature in each, but not to the same extent. In the northern hemisphere the sea covers an area one and a half times as large as the land, but in the southern hemisphere the area covered by the sea is four times as large as the land. This difference in the relative proportion of land to sea is even larger for the temperate zones in the two hemispheres than for the hemispheres themselves. Taking the four ten-degree zones between latitudes 20° and 60° as constituting the temperate zones, we find from the table that in the northern hemisphere the sea in these latitudes covers an area but little greater than the land, while in the southern hemisphere in these latitudes the sea covers an area eight times as large as the land. The distribution of land and sea is therefore such that the northern hemisphere offers a much greater area suitable for the habitation of man; and this finds reflection in a

population five times as large in the northern hemisphere as in the southern.

The distribution of land and sea in the different latitudes has been very strikingly pictured in a map by Albert Baldit, a French scientist. After computing the areas of land and sea for each degree of latitude between 80° N. and 65° S., he conceived the land areas within each such degree zone to be joined together into a continuous land mass symmetrically placed with respect to a central meridian. This map is reproduced in Figure 3 and brings out clearly the features characterizing the distribution of land and sea within those latitudes and the differences in this distribution in the two hemispheres.

The maps which we meet with most frequently are those drawn on the Mercator projection, in which both latitude and longitude lines are shown as straight lines perpendicular to each other. This general use of the Mercator projection is due to a number of advantages it possesses, especially for the navigator. To secure these advantages, however, this projection is compelled to distort areas in different latitudes. In maps drawn on the Mercator projection equal areas on the earth's surface in different latitudes are shown as unequal, areas in the higher latitudes being greatly exaggerated. It should therefore be noted that the map of Figure 3 is drawn on the so-called sinusoidal projection in which equality of area is preserved. On this map areas in different latitudes are directly comparable.

The conception of a northern hemisphere and a southern hemisphere we have come to regard as valid, as dividing the earth into two parts of contrasting astronomic and climatic conditions. With regard to the existing distribution of land and sea some geographers have urged the conception of a land hemisphere and a marine hemisphere, that is, of a division of the earth into hemispheres such that one contains the maximum land area and the other

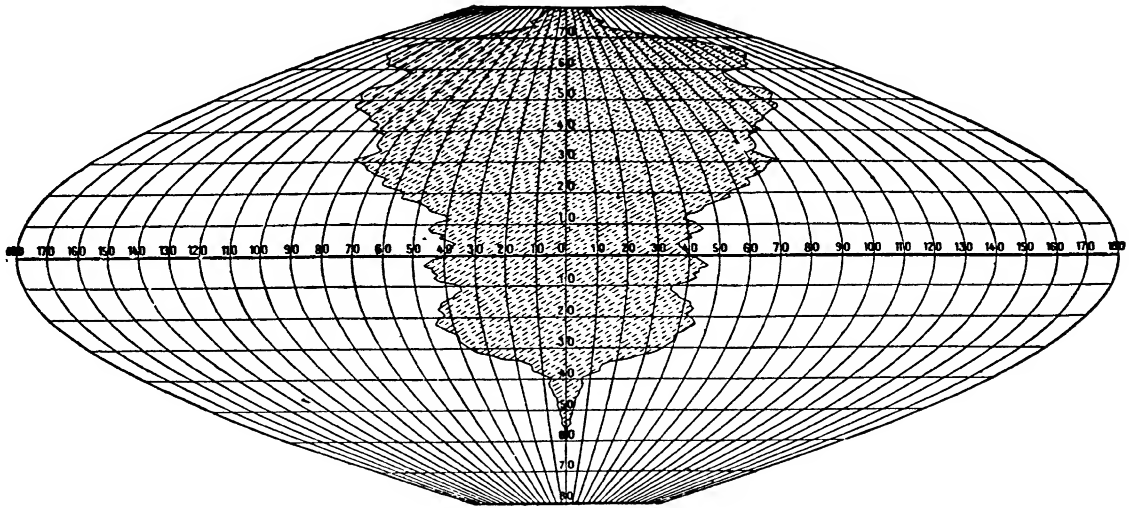

FIG. 3.—RELATIVE AREAS OF LAND AND SEA BETWEEN LATITUDES 80° N. AND 65° S. (AFTER BALDIT)

the maximum water area. The land hemisphere is found to have its pole on the Atlantic coast of France, between St. Nazaire and Quiberon in, approximately, latitude 47½° N., and longitude 2½° W. The marine hemisphere therefore has its pole in latitude 47½° S. and longitude 177½° E., which places it in the South Pacific Ocean about four hundred miles east of the southern end of New Zealand. But even of this land hemisphere the sea constitutes the greater part—about 55 per cent—while the land forms 45 per cent. In the marine hemisphere the sea covers about 90 per cent of the area, the land occupying but 10 per cent.

With the pole in 47½° north latitude and 2½° west longitude it is obvious that the land hemisphere contains all of Europe, all of Africa, all of Asia with the exception of some detached parts, all of North America and the greater part of South America. Of the lands of the earth, the marine hemisphere contains only Australia, the islands of Oceania, the Antarctic and small portions of Asia and South America.

As we shall see later, the rôle of the sea in the economy of nature is of very great importance. Should not such striking differences in the distribution of the sea as between the land and marine hemispheres find reflection in the physical environment and hence in the life of the two hemispheres? As a matter of fact, it does. It is, perhaps, not without significance that the pole, or center as it were, of the land hemisphere is found in western Europe, the influence of which in modern civilization has been so pronounced. On comparison, the climatic conditions in the marine hemisphere are found more stable but at the same time more severe. It is in the marine hemisphere—in the southern seas—that the mariner meets with the highest waves and the most violent tempests. Atmospheric conditions in the land hemisphere are less stable and of greater variety—better suited for evoking a vigorous life.

Notwithstanding the great preponderance of the sea and the fact that it forms a single sheet of water, the land masses of the old and new worlds are sufficiently extensive to separate out oceanic basins which are distinct enough to bear individual names. Thus we recognize the three great oceans, the Atlantic, the Pacific, and the Indian. The northern limits of these oceans are definitely marked out by land boundaries; but toward the south they merge into a single, great belt of water which completely encircles the world.

In the division of the earth into land and sea no regularity appears to obtain. It is a striking fact, however, that there is a certain balance between land and sea in that, roughly, the continental land masses lie opposite the oceans. Thus, the Antarctic continent balances, as it were, the Arctic Sea, while the wide extent of the Pacific is similarly balanced by the great land mass of the Old World. In fact, it appears that only one-twentieth part of the continental land masses has land facing it on the opposite side of the earth, while the other nineteen-twentieths are balanced by water.

The mobility of the waters constituting the sea permits the continental land masses to impose their outlines upon the oceans; and thus arise the characteristic shapes of the oceans. The Atlantic Ocean, with its westward bulge in the middle northern latitudes and its eastward bulge south of the equator, bears some resemblance to the letter S. The Pacific Ocean is roughly elliptical in outline, and the Indian Ocean may without too great a stretch of the imagination be considered as semicircular in outline.

Around the edges of the oceans, islands and continental land masses separate out various smaller bodies of water to which such names as seas, gulfs, bays, etc., have been applied. To the professional oceanographer it is of interest to classify these bodies of water according to various

schemes; but for our purposes here it will be sufficient to recognize but a twofold division of the world-embracing sea, namely, the independent oceans and the dependent seas. The oceans are characterized by wide extent and, as we shall see later, by relatively great depths; the dependent seas are much smaller in area and much shallower. In the following table the areas of the three oceans and of some of the better known seas and smaller bodies of water are given. Here, too, it will be sufficient to give the areas to the nearest hundred thousand square miles, that is, to the nearest tenth of a million square miles.

AREAS OF THE OCEANS AND OF VARIOUS SEAS

Name	Area (million sq. miles)	Name	Area (million sq. miles)
Pacific Ocean	63.8	Okhotsk Sea	0.6
Atlantic Ocean	31.8	East China Sea	0.5
Indian Ocean	28.4	Hudson Bay	0.5
Arctic Sea	5.5	Japan Sea	0.4
Mediterranean Sea	1.0	North Sea	0.2
Caribbean Sea	1.0	Red Sea	0.2
Bering Sea	0.9	Baltic Sea	0.2
Gulf of Mexico	0.6	Persian Gulf	0.1

The table brings out clearly the striking differences in area between the oceans and the dependent seas. The Arctic, it will be noted, is classed not with the oceans but with the seas; for on the score of area alone it is seen that it does not belong with the oceans. Of the total expanse of the sea, the three oceans constitute 90 per cent while all the dependent seas together make up only the remaining 10 per cent.

We have found that the three oceans differ in shape, and the table above shows that they differ also in area. The Pacific Ocean is the greatest and covers an area somewhat

larger than the other two combined. Both the Atlantic and the Pacific differ from the Indian in that the latter has a relatively narrow extension in latitude, while the former stretch from one polar circle to the other. The Indian Ocean differs also in another respect from the other two oceans. Only on its northern boundary does it make any deep indentation into the land. The Atlantic and Pacific oceans, however, have their deepest indentations on the eastern and western shores.

Each of the three oceans has its surface broken here and there by islands. But in this regard, too, they exhibit characteristic differences. With the exception of the Malay Archipelago, which forms its eastern boundary, the Indian Ocean is relatively poor in islands. The Pacific Ocean, in striking contrast, is studded with islands and groups of islands. The Atlantic occupies an intermediate position, having more islands than the Indian but less than the Pacific.

A study of each ocean brings out important differences in the extent to which it penetrates its land boundaries. The Atlantic, for example, in its northern half penetrates the land at a number of points both on its eastern and western shores; while in its southern half there are but few indentations. In the Pacific we have a different arrangement, the contrast being between the eastern and western shores. The latter are well indented while the former have but few indentations.

The extent to which an ocean penetrates its shores has been of considerable importance in history. On the one hand, a broken, indented coast means that the ameliorating and vivifying influences of the sea are spread over a wider area. On the other hand, it means the existence of harbors to serve as bases for fisherman and world-trader, and of conditions that develop maritime enterprise. Contrast the rôles played on the stage of history by the peoples on the

deeply indented coasts of western Europe and those on the unbroken shores of Africa. As a highway of commerce and intercourse the Atlantic is the principal ocean. It is, therefore, not without significance that the Atlantic Ocean has a coast line greater than that of the Pacific and Indian oceans taken together.

The detailed study of the contours of the different oceans lies outside the scope of this volume. Before closing the chapter on the extent of the sea, however, it is necessary to note that no land boundaries of any kind separate the three oceans southward of the great land masses, toward the Antarctic. Here they merge into a single belt of water that completely encircles the earth. Just where the boundaries of each ocean are to be drawn here is obviously somewhat arbitrary. But a strong case can be made out for separating the Atlantic from the Pacific by the meridian that runs through Cape Horn, the Pacific from the Indian by the meridian through South Cape, Tasmania, and the Indian from the Atlantic by the meridian through Cape Agulhas.

It has been customary to speak of the belt of water that completely encircles the earth southward of the great land masses as the Southern or Antarctic Ocean. It has also been found convenient to divide both the Atlantic and the Pacific into northern and southern parts. That the terms used with regard to these areas may have definite meanings, the International Hydrographic Bureau has suggested definite though necessarily somewhat arbitrary limits for the various oceanic areas and smaller divisions of the sea. The boundaries for forty-eight different bodies of water are shown on the map accompanying the circular letter of the International Hydrographic Bureau issued in 1923 under the title "Limits of Oceans and Seas." It is of interest to note that the southern boundary of the South Atlantic, South Pacific and Indian oceans is fixed by the

latitude of 60° S., the water to the southward being designated as the Antarctic Ocean. Similarly, the northern limit of the North Atlantic is fixed at the latitude 60° N., the waters northward being called the Arctic Ocean.

CHAPTER VIII

THE DEPTHS OF THE SEA

FROM early times the depth of water under his ship has been a matter of concern to the navigator; for the safety of the life and property in his care depended on a sufficient depth of water for the draft of his vessel. But it was not so much with the actual depth that he was concerned as with a depth sufficient for safe navigation. As long as he was assured of this depth, the actual depth of the water became a matter of academic interest. As a consequence, we find the ancients acquainted, almost without exception, with depths in coastal waters only.

The simple and time-honored method of determining depths is by means of the hand lead. Essentially, this consists of a piece of some heavy metal, lead for example, fastened to a line graduated in fathoms. The fathom—six feet—is approximately the distance between the finger tips of a man's outstretched arms. And frequently the seaman tested his line by measuring it between thumb and forefinger of each hand. In "heaving the lead" it is allowed to drop through the water, and as it strikes bottom the seaman is made aware of the fact by the change in the tension of the line.

The difficulty of sounding with the hand lead in deep water is obvious and as late as the middle of the seventeenth century we are informed by a geographer of the time that he had not been able to find a single mariner who had sounded depths greater than two hundred fathoms. In this connection it is of interest to note that Magellan, in

1521, while crossing the Pacific Ocean, attempted a deep-sea sounding. His sounding line, which may have had a length of something like four hundred fathoms, did not reach the bottom, and he therefore concluded that he had there discovered the deepest part of the ocean.

Before the end of the eighteenth century, however, we have record of successful deep-sea soundings. In 1773 an English navigator, Captain Phipps, made a sounding of 683 fathoms in the Arctic Sea. The apparatus used was very simple. All the sounding lines on board were spliced together and attached to a weight of 150 pounds. On being dropped into the water this weight carried the line down at a relatively rapid rate, the sudden slackening in the rate indicating the instant when bottom was reached. About three-quarters of a century later—in 1840—Sir James Clark Ross in the Antarctic sounded depths of over 2,600 fathoms, or a little more than three miles.

The sounding lines used at this time were of stout hemp, a quarter of an inch or more in diameter. A line of this kind, several miles long, was heavy, bulky and expensive. With this outfit, sounding was also a time-consuming job. While taking a sounding it is necessary that the vessel remain stationary, and in the days of the sailing vessel this meant that all sail had to be taken in. Furthermore, the mere paying out and hauling in of the line took several hours. The weight and size of the line also introduced a number of sources of error—the weight causing it to sag in the water and the considerable surface furnishing sufficient area for currents to add to the sag. Nor was it easy to determine when the lead struck bottom. In two different places in the South Atlantic Ocean, Sir James Clark Ross recorded no bottom reached after 4,000 fathoms of line had run out, where later soundings showed bottom at two-thirds that depth.

About the middle of the nineteenth century, improve-

ments in the method of sounding began to be introduced. The American naval officer, Matthew Fontaine Maury, substituted twine for the cumbersome hemp lines. By attaching a cannon ball to this line it was run out rapidly and when bottom was touched the twine was cut, no attempt being made to haul the weight from the bottom of the sea. About this time, too, the question of the depths of the oceans became a matter of practical concern in connection with the laying of telegraph cables. Various improvements in sounding apparatus followed and in the early seventies steel piano wire was introduced in place of twine or rope by the English physicist, William Thomson, better known as Lord Kelvin.

As finally developed for deep-sea work, sounding machines make use of steel piano wire about one-twentieth of an inch in diameter, which is wound on a drum. The wire passes over a pulley which is calibrated to give the number of fathoms of wire run out. The sinker used weighs about fifty pounds and is so arranged that it detaches itself from the sounding wire as soon as it strikes bottom, for, if it were necessary to reel in the wire with the sinker attached, the strain would be too great for the wire. The sinker is fitted around a tube or other contrivance firmly attached to the wire, which plunges into the bottom. The sample of the bottom brought up by this means not only furnishes material for the study of the nature of the bottom of the sea, but also gives definite evidence that bottom has been reached. The sounding machine is further fitted with adjustments which automatically stop the unwinding of the wire from the drum. the moment the bottom of the sea is reached.

But even with the modern sounding machine the determination of depths in the sea is a costly and time-consuming operation. The ship must be brought to a stop before the wire can be run out and it must remain stationary, too,

very nearly all the time the wire is being reeled in, otherwise the strain on the wire may become too great. With a motor-driven sounding machine—one of the latest types—a sounding of 3,000 fathoms takes an hour and a half, of which half an hour is required for the descent of the wire and an hour for the reeling in. A sounding of 5,000 fathoms takes about three hours.

Cannot ocean depths be determined by some less costly and less time-consuming means? Various schemes have been proposed from time to time. At an early date an arrangement of two bodies was suggested, one heavier and the other lighter than water, so united that when dropped into the water they would sink together, but on touching the bottom the lighter body would be released and rise to the surface. The depth was then to be calculated from the time required by the apparatus to sink and rise again to the surface. While ingenious, the difficulties involved in this scheme are of such a nature as to preclude its use altogether. Sounding tubes, in which the depth is determined through the pressure of the water against an enclosed column of air may be used for moderate depths; the great pressures in oceanic depths render the sounding tube useless for such depths.

Since the World War a practical method for determining oceanic depths by means of sound waves has been perfected. This so-called sonic method of sounding depends on measuring very accurately the time interval taken for a sound to be echoed from the sea bottom. An apparatus installed in the ship is made to emit a sound which on reaching the bottom of the sea is reflected as an echo. This reflected sound on reaching the ship is recorded by a receiving apparatus. The velocity of sound in water being known, it is obvious that when the time interval between the emission of the sound wave and the reception of its echo is known, the depth of water can be readily calculated.

Indeed, in some types of sonic sounding machines the calculation is performed automatically, the depth being shown immediately on the face of the machine.

The sounding of the ocean depths by means of sonic depth finders is an outstanding advance. For not only is it more rapid—where a deep-sea sounding with wire was a matter of hours, a similar sonic sounding is a matter of minutes—but what is even of greater importance, it can be accomplished while the ship is under way. It is to be borne in mind, however, that our knowledge of the depths of the ocean to the present time has come from the laborious use of the sounding lead with its miles-long line of hemp, twine or wire.

In connection with the hydrographic surveys of the coasts under their jurisdiction the various maritime nations have made a very considerable number of soundings. But these are all close to the coast and therefore in relatively shallow depths. Out in the open oceans soundings are much less frequent. An actual count of all soundings greater than 3,300 feet or 550 fathoms recorded to the time of the introduction of sonic sounding methods gave a total of 15,000 in round numbers. Of these 6,100 are in the Atlantic, 6,300 in the Pacific and 2,500 in the Indian Ocean.

That these 15,000 deep-sea soundings are not equally distributed over the open sea is evident from the fact that the Atlantic Ocean has very nearly as many of these soundings as the much larger Pacific. If we take into consideration only those areas in the oceans which have depths greater than 3,300 feet, it is found that in the Atlantic Ocean there is one deep-sea sounding for each 5,500 square miles, in the Indian Ocean one such sounding for each 10,500 square miles, and in the Pacific Ocean one for each 10,000 square miles. This means that in the Pacific Ocean there is, on the average, but one sounding for areas larger

than that of the State of Massachusetts or of New Jersey and very nearly as large as all of Belgium.

Now the average density of the deep-sea soundings, considered in the previous paragraph, obviously does not tell the whole story with regard to the distribution of these soundings. Within the regions of the more moderate oceanic depths the number of soundings is relatively much greater than in the regions of greatest depth. Furthermore, the soundings are not evenly spaced, being most dense along lines of soundings made in connection with the laying of telegraph cables. If the 15,000 deep-sea soundings are plotted as dots on a chart of the oceans, the resulting picture is that of a net of irregular mesh. Such a picture brings out clearly the scarcity of the soundings in the open sea, for a number of the meshes are nearly as large as all of Europe. There is, therefore, still a great deal of work remaining to be done in charting in detail the features characterizing the depths of the oceans.

While the soundings in the open sea are relatively scarce, these soundings, together with the more numerous soundings near the coast and in the dependent seas, give us a fairly comprehensive picture of the depths of the sea. From these soundings the oceanographer has been able to make a so-called bathymetric chart of the oceans, that is, a map showing the depths of the oceans. Such a map cannot yet claim to give in great detail the varying depths of the sea, but that the larger features and general characteristics are now well known cannot be questioned. From such a bathymetric chart the average depth of the sea can be determined, the latest calculation giving 12,450 feet, or 2.36 miles.

A word of explanation with regard to figures dealing with the area and depth of the sea is perhaps necessary here. As already emphasized, the area of the sea is known only in round numbers. This fact, together with the fact

that the soundings in the open sea are still relatively scarce, makes it clear that at the present time it is only in round numbers that we know the average depth of the sea. In taking this depth at 12,450 feet it is not to be understood that it is known to the nearest ten feet. Indeed, if the depth alone were in question it would be better to take it as 12,500 feet, which figure would more nearly indicate the approximate character of the average depth. But we want to use the depth in deriving the volume of the sea; and as the latest calculation gives 12,450 feet for the average depth our value derived for the volume of the sea will be more nearly correct if we use that figure for the depth.

As regards extent, we have found the sea with an area of 139½ million square miles to be about two and one-half times as large as the land with its area of 57½ million square miles. How do land and sea compare as regards volume? With an average depth of 2.36 miles, the volume of the sea comes out as 329 million cubic miles. For the land it has been computed that its average height above sea level is 2,750 feet or 0.52 mile. With this value the volume of the land above sea level comes out just a little under 30 million cubic miles. The volume of the ocean is, therefore, eleven times that of the land.

In our consideration of the extent of the sea in the preceding chapter, we found that as between the two hemispheres the southern contained the larger part of the sea, while the northern had the larger part of the land. Coming now to a consideration of average depth we find the southern hemisphere again ahead of the northern, the former having an average depth of 2.49 miles or approximately 13,000 feet while the latter has a depth of 2.24 miles or, in round numbers, 12,000 feet. The sea in the southern hemisphere is thus a quarter of a mile deeper on the average than in the northern hemisphere.

With a larger extent of sea, and also with a greater

average depth, it follows that the volume of the sea in the southern hemisphere must be greater than in the northern. In the former the sea covers an area of 79.7 million square miles with an average depth of 2.49 miles, which gives the southern sea a volume of 198 million cubic miles. In the northern hemisphere, the sea with its area of 59.7 million square miles and average depth of 2.24 miles occupies a volume of 134 million cubic miles. The southern sea thus

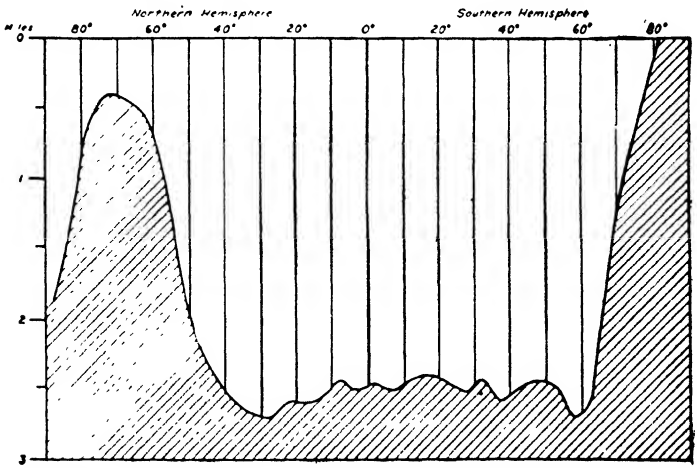

FIG. 4.—AVERAGE DEPTH OF THE SEA FOR EACH FIVE-DEGREE ZONE OF LATITUDE

has a volume very nearly half as large again as the northern sea.

If now we investigate the distribution of the average depth in the different latitudes, we find that the greater average depth of the sea in the southern hemisphere is due not to the existence of greater depths but to a greater extension of considerable depths. This is clearly brought out in Figure 4 in which the average depth for each five-degree zone of latitude is given.

A glance at Figure 4 brings out the fact, that, so far as

average depth over five-degree zones of latitude are concerned, the northern hemisphere can boast of as great depths as the southern. But while the southern hemisphere has an average depth of very nearly two and one-half miles from the equator all the way to the 65th parallel of latitude, the northern hemisphere can show this average depth from the equator only as far as the 40th parallel of latitude.

For the earth as a whole we have found that in area, in average depth as contrasted with average elevation, and in volume, the sea outranks the land considerably. But from earliest times there appears to have been a feeling that the depths in the sea correspond with the heights on land. The geographer Bernhard Varenius states this in his *Geography* which appeared in 1650, as follows:

> Moreover, from the Observations of the Depth in divers Places, it is manifest, that the Channels in Depth are nearly equal to the Mountains and inland Parts in Elevation, that is, as much as the one is raised, so much the other is depressed, and as the Altitude of the inland Parts is gradually increased from the Shore, so is the Sea deeper and deeper towards the Middle of the Ocean, where the Depth is for the most part greatest.[1]

At the time Varenius wrote, no deep-sea sounding had yet been made; but the assumption of a similarity between heights on land and depths in the sea has since been found to be largely correct. The greatest elevation of the land is found among the lofty Himalayas, Mt. Everest towering 29,100 feet or 5.5 miles above the level of the sea. The greatest depth to date was found by the German cruiser *Emden* in the North Pacific Ocean about forty miles east of the Philippine Islands. Here on April 29, 1927, a sonic sounding gave a depth of 35,400 feet or 6.7 miles. While the deepest point in the sea is thus greater than the high-

[1] From Dugdale's translation (1734), Vol. I, p. 201.

est point on land, the difference between them is nothing like as great as the difference between land and sea in regard to area or volume.

When we come to a comparison of the depths in the various subdivisions of the sea we find, as in the case of their areas, the sharp line of demarcation between the independent oceans and the dependent seas. The Pacific Ocean heads the list with an average depth of 14,050 feet or 2.66 miles; the Indian Ocean comes next with an average depth of 13,000 feet or 2.46 miles and the Atlantic Ocean follows closely with an average depth of 12,880 feet or 2.44 miles. For the Arctic Sea, the largest of the dependent seas, our present knowledge gives an average depth of 3,950 feet or 0.75 mile, while for the Mediterranean, the next largest of the dependent seas, the average depth is somewhat greater, but still less than a mile.

It will be of advantage to list the average depths of the oceans and of the more important dependent seas in tabular form so that comparisons may be readily made. And though the areas of these bodies of water have already been given in the preceding chapter it will be convenient to list these in connection with the average depths, since this will permit the volumes to be readily computed. And to complete the picture, the greatest depth in each body of water will be listed. In the table following, these data are given for the oceans and the more important dependent seas.

Glancing down the column of average depths, the eye is caught by the sudden drop between the oceans and the dependent seas. Measured in feet it requires five figures to represent the average depth of each of the oceans, while four figures are sufficient for expressing the average depth of even the very deepest of the dependent seas. Nevertheless, it must be noted that, as regards average depth, the difference between oceans and seas is not nearly so great as the like difference in area. Thus, the Pacific Ocean covers

an area of more than sixty times as large as the Mediterranean; its average depth, however, is but three times as great.

As a rule, land and sea meet on a gradually shelving shore, the depth increasing seaward with more or less regularity. We should, therefore, expect that of two bodies of water the one having the greater extent would also have

AREAS, DEPTHS AND VOLUMES OF THE OCEANS AND OF VARIOUS SEAS

Name	Area (million sq. miles)	Average Depth (feet)	Volume (million cu. miles)	Greatest Depth (feet)
Pacific Ocean	63.8	14,050	169.8	35,400
Atlantic Ocean	31.8	12,880	77.6	27,970
Indian Ocean	28.4	13,000	69.9	22,970
Arctic Sea	5.5	3,950	4.1	18,400
Mediterranean Sea	1.0	4,690	0.9	14,450
Caribbean Sea	1.0	8,670	1.6	20,570
Bering Sea	0.9	4,710	0.8	12,920
Gulf of Mexico	0.6	4,880	0.6	12,500
Okhotsk Sea	0.6	2,750	0.3	11,060
Hudson Bay	0.5	420	0.04	750
Japan Sea	0.4	4,430	0.3	12,180
North Sea	0.2	310	0.01	2,220
Red Sea	0.2	1,610	0.06	7,740
Baltic Sea	0.2	180	0.01	1,520

the greater depths. And as a general rule this is borne out by the figures in our table above. The oceans and seas in this table are listed in the order of their areas. But a glance down the column of average depths discloses the fact that these likewise are ranged roughly in their natural order.

As regards volume, it is obvious that, since this is a product of area by average depth, the disparity between oceans and seas must be even greater than in regard to area. The smallest of the oceans, it is seen, has a volume

more than 15 times as great as the largest of the seas. It will be noted, too, that in ranging the subdivisions of the sea in accordance with area ranges them also, very closely, in the order of volume.

An inspection of the column of greatest depth shows that in this respect, too, oceans and seas are in different classes. But, with regard to this feature, the difference is not so marked as with regard to area, average depth or volume. Thus the Caribbean Sea, with an area less than one-twentieth that of the Indian Ocean and with a volume only one-fortieth as large, boasts an extreme depth very nearly as great. With regard to greatest depth, too, we find, generally, the greater the body of water, the greater the extreme depth. So that when the subdivisions of the sea are ranged in the order of their areas, they become ranged, approximately, in the order of their greatest depths.

A comparison of the areas or volumes in our table with the corresponding greatest depths shows that, while as a rule the larger the body of water, the greater the depth, no simple numerical relation holds between them. The greatest depth in the Pacific Ocean in thousands of feet is approximately half the area expressed in millions of square miles, or as one is to one-half. But for the Caribbean Sea this relationship is as one is to twenty. Between the average and greatest depths, however, an approximate ratio does exist, for it will be seen that, as a rule, the greatest depth in any of the oceans or larger seas is from two to three times the average depth. This, however, is only a general rule, for in certain seas, as, for example, the Arctic, North, and Baltic, the relation between average and greatest depths is quite different.

It is, thus, a great variety of depths that the sea exhibits, from those measured in single feet along the coast to those measured in tens of thousands of feet in the abysses of the oceans. The average depth of the sea and its greatest depth

we have already considered. Now we are confronted by the question of the relative areas occupied by the different depths. How large a part of the sea is covered by depths less than a mile? Is this area greater or less than that covered by depths in excess of three miles? How large a feature is constituted by depths in excess of five miles?

Tables listing the areas occupied by the different depths of the sea have been prepared and may be consulted in

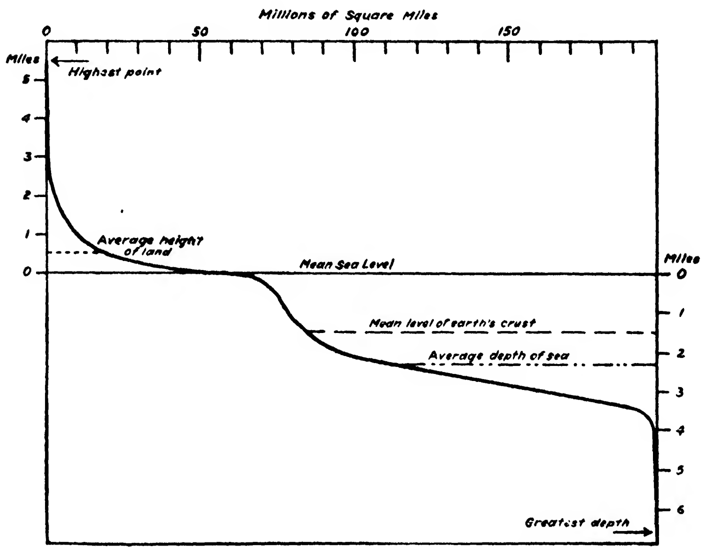

FIG. 5.—HYPSOGRAPHIC CURVE OF THE EARTH'S SURFACE

various publications. But much more illuminating than the figures of such tables is the diagrammatic representation in the form of a curve as reproduced in the lower curve of Figure 5. Depths are measured vertically downward in accordance with the scale of miles to the right while areas are measured horizontally in accordance with the scale of millions of square miles at the top. This curve becomes even more instructive, if we join to it the similar curve

which gives the areas occupied by the different heights on the land, which is represented by the upper part of the curve in Figure 5. With respect to this curve, heights are reckoned vertically upward from mean sea level in accordance with the scale of miles to the left and areas, as before, in accordance with the scale at the top. This curve of relative areas of heights on land and depths in the sea is an important one and is known as the hypsographic curve.

The hypsographic curve brings out clearly a number of the features that characterize the depths in the sea and permits of ready comparison with the features that characterize the heights on land. At a glance we see that the greatest depth of the sea does not differ very much from the highest point on land; that the greater part of the sea has a depth in excess of one mile while the greater part of the land has an elevation less than a mile; that the area of the sea with depths of more than four miles is a very small fraction of the extent of the sea.

The land is exposed to forces which tend to reduce its elevation and carry the material of which it is composed into the sea. Were there no counterbalancing forces, the sea would in time cover the whole earth. Suppose that the earth's crust were leveled, how deep a layer of water would the sea provide? The hypsographic curve permits us to determine this readily, the depth of the earth's crust below mean sea level being indicated by the broken line. If all the inequalities in the heights on land and depths in the sea were leveled off, the earth would be covered by a layer of water with a depth of one and one-half miles.

CHAPTER IX

THE BOTTOM OF THE SEA

In studying the surface features of the earth's crust, the line that divides the sea from the land marks at the same time the dividing line between two regions in which the methods used in the one are no longer applicable in the other. On the land the surface features stand revealed before our eyes and we are enabled to make direct measurements and comparisons. In the sea the surface features of the earth's crust lie hidden from our gaze; so that it is only by indirect methods that we can gain knowledge of the features that characterize the bottom of the sea.

The data that will enable us to picture the appearance of the bottom of the sea are obviously furnished by the depths of the sea. Indeed, in our consideration of these depths in the previous chapter we were tracing out at the same time the features of the sea bottom. Our interest was, however, with the depth of the water, and our point of view was, therefore, from the surface of the sea. Now it is the bottom that claims our interest. What would be the appearance of the bottom of the sea, if we were enabled to view it in the same way that we can the surface of the land?

If we take a map of any of the oceans or seas on which the depths have been plotted we can, by a painstaking study of these plotted figures, arrive at an understanding of certain of the features of the bottom of that body of water. If, however, instead of confining ourselves to the figures alone we make use also of contour lines, that is, of lines

joining equal depths, our study is made very much easier. For the contour lines enable us to view the relief of the bottom of the sea over extensive areas. By their direction the contour lines tell at a glance the direction of slope of the bottom; by their spacing they reveal whether or not the slope is uniform. Sudden changes in relief are pictured by the crowding together or spreading apart of the contour lines, and thus hills, valleys, and plains on the sea bottom become visualized for us.

The conception of contour lines for representing the relief of the earth's surface is a very fruitful one, and is applicable equally to land and sea. But it is of interest to note that it appears to have been first employed in connection with the sea and not with the land. Apparently contour lines were first used by the Dutch surveyor, Cruquius, in 1728 in connection with a chart of the river Merwerde; they are frequently credited, however, to the French geographer Philippe Buache, who used them for representing depths in the sea on a map published in 1737. At the time that Buache was studying the matter no deep-sea soundings had yet been made. Reasoning by analogy from the features on land, he concluded that the bottom of the sea is crossed by chains of mountains which, together with those on land, form the framework of the earth as it were, helping to increase its rigidity. In his view the bottom of the sea repeated the features we find on the land, the oceanic islands representing but the peaks of submarine mountains.

Our knowledge of the features of the bottom of the sea has increased very greatly since Buache's time. Detailed studies of the depths of the different oceans and seas have been made, so that in spite of the relative scarcity of deep-sea soundings, the general features of the oceanic basins may be considered as known. These studies bring out the fact that in a number of respects the basins of the different oceans and seas differ, each exhibiting individual charac-

teristics. But what is of more importance for our study of the sea is the fact that certain features are generally found in all the bodies of water that make up the sea; and it is these general features that characterize the bottom of the sea that we must now consider.

From the shores which form the boundary of the sea, the bottom is found to slope gradually until a depth of something like 100 fathoms is reached, when the slope becomes steeper. This zone which, in a sense, marks the transition from land to sea is known as the continental shelf. Manifestly, the limit of 100 fathoms is somewhat arbitrary, but it is a round, easily remembered figure and defines with sufficient approximation an important feature of the sea.

It should be clearly understood that it is the sudden change in slope and not the depth of 100 fathoms that defines the continental shelf. In some places this change in slope may occur at a depth of but 50 fathoms and at others not till 150 fathoms is reached. But, as a general rule, 100 fathoms may be taken as marking the seaward boundary of the shelf.

The width of the continental shelf varies considerably from place to place. A glance at a chart on which the 100-fathom line is plotted shows it following the coastline at varying distances. Thus, along the Atlantic coast of the United States the 100-fathom line is about 60 miles off the coast of Maine, 75 miles off New York, 60 miles off South Carolina, and only 5 miles off southeastern Florida. In the Gulf of Mexico the 100-fathom curve lies at a distance from the coast varying from 10 miles to more than 100 miles; on the Pacific coast of the United States it varies in distance from less than 5 miles off southern California to 40 miles off the State of Washington.

In certain regions the continental shelf extends out to sea for very considerable distances. Southward and east-

ward from Newfoundland the bottom slopes so gradually that it is 250 miles from shore before the 100-fathom line is reached. This extensive area, which is known as the Great Bank of Newfoundland, constitutes one of the most important fishing grounds in the world. The Arctic Sea furnishes an example of an even more extensive shelf, for along the coast of Siberia the 100-fathom line lies from 300 to 400 miles offshore.

It is on the continental shelves that the great sea fisheries are found. The Great Bank of Newfoundland has already been mentioned as one of the most important fishing grounds. The North Sea furnishes another example. The banks of this sea constitute an immensely valuable treasure house, from which enormous quantities of fish have been taken for more than five hundred years. And it is not difficult to see why it is that the great fishing grounds should lie on the continental shelf. For here the water is relatively shallow, allowing the sunlight to penetrate to the bottom. Much of the shelf is therefore covered by an abundant growth of marine plants which furnish food for the fish. It is on the shelf, too, that the river waters deposit their freight of fish food which they gathered on their way to the ocean.

From the continental shelf the sea bottom slopes more steeply, the gradient being most pronounced at a depth of about 1,000 fathoms. This part of the sea bottom is known as the continental slope. On a chart the steeper gradient of the continental slope is evidenced by the crowding together of the contour lines. Thus, off the Atlantic coast of the United States the 100-fathom line, from Maine to South Carolina, lies approximately 50 miles offshore. Were the slope to remain constant, it would be 500 miles offshore that the 1,000-fathom line would be found, whereas it is actually found less than 100 miles from shore.

Beyond the continental slope the bottom of the sea again

slopes very gradually to the abysses which form the characteristic feature of the bottom—great flat plains of enormous extent. Nowhere on land do we find such vast plains as the sea bottom presents. Turning back to the hypsographic curve shown in Figure 5, we see that by far the larger part of the sea bottom lies between one and one-half and three and one-half miles below sea level.

From general considerations, it would appear that the relief of the earth's crust should be much less diversified in the sea than on land. For the waters so blanket the sea bottom that it remains undisturbed by a number of agencies which act vigorously on the surface of the land. Rain, frost and wind—active agents in molding the relief of the land—leave untouched the bottom of the sea. The land is also subject to the constant wear and tear of running water, from which the sea bottom is free; for over the bottom of the sea the currents are much gentler, and are not confined in ever-deepening channels, as they are on the land.

Along the coast the bottom of the sea reflects to a large extent the character of the neighboring coast. When the coast is flat and sandy, the bottom of the sea will likewise be uniform and sandy. And where the coast is bold and rocky the neighboring waters will, as a rule, be dotted with rocks and boulders. But even here the net resultant of the forces at work is toward greater uniformity of the bottom of the sea.

It is not that the bottom of the sea presents no instances of great diversity in relief, but rather that such cases are the exception rather than the rule. Wherever an island rises from the ocean depths it is obvious that the gentle rhythm of the relief of the sea is broken. The submarine channels of large rivers may likewise give rise to bold relief. Thus the channel of the Hudson River is continued in the sea by a gorge for a distance of a hundred miles, the bottom

of this gorge being in some places more than two thousand feet deep.

The vast extent of the sea bottom, however, is undoubtedly characterized by gentle relief. It has been customary to emphasize this by statements to the effect that if a trip by carriage on the bottom of the sea were possible, say from Brest to New York, the slopes encountered would be so gentle as to be unrecognized. In this connection, however, it must be remembered that over the greater part of the sea only scattered soundings are at hand. Furthermore, until very recent years the sounding lead furnished the only means available for determining depths within the sea.

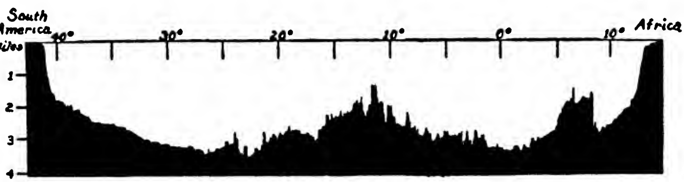

FIG. 6.—PROFILE OF THE SOUTH ATLANTIC OCEAN ALONG THE 22ND PARALLEL (ADAPTED FROM DEFANT)

And the sounding lead from its very nature can bring out only the larger features of the relief within the deeper parts of the sea. The sonic soundings in the South Atlantic Ocean by the recent German oceanographic expedition on the *Meteor* make it appear that the gentleness of relief of the sea bottom may have been very considerably overestimated.

In Figure 6 we have a profile of the sea bottom across the South Atlantic Ocean approximately along the twenty-second parallel of latitude, as determined by sonic soundings on the *Meteor*. Because the horizontal distance from South America to Africa is so much greater than the depths of the sea, it is necessary to use a much reduced horizontal scale as compared with the vertical scale. In fact, in the

figure the vertical scale is 185 times as large as the horizontal scale. Slopes are, therefore, much exaggerated. Nevertheless, it is clear at a glance that the relief of the sea bottom here is far from gentle.

Detailed studies of the beds of the individual oceans and seas make use of various technical terms in describing the different forms of relief. An area of shallow water, especially one on which the sea breaks in heavy weather, is known as a shoal. A bank is a large non-rocky shoal with a sufficient depth of water to prevent the sea from breaking over it. A rocky submarine elevation of elongated form, especially one dangerous to navigation, is called a reef. Depressions greater than three thousand fathoms (18,000 feet or 3.4 miles) are known as deeps.

The detailed study of the beds of the individual oceans and seas falls outside the scope of the present volume, but it will be of interest to notice the deeps briefly. Turning back again to the hypsographic curve, it is seen that depths greater than 3.4 miles cover something like one-fourteenth, or approximately 7 per cent, of the sea bottom. At the present time 57 deeps are known. They are generally designated by the name of some oceanographer or by the name of some exploring ship. Of these 57 deeps, 32 are in the Pacific, 19 in the Atlantic and 6 in the Indian Ocean. They vary greatly in shape and size, some of them, however, covering very considerable areas. Thus the Valdivia Deep, which lies partly in the Atlantic and partly in the Indian Ocean, covers an area of more than one million square miles. The Murray Deep which lies in the central part of the North Pacific Ocean also covers an area of more than a million square miles.

The mariner frequently makes use of the varying topography of the sea bottom for locating the position of his vessel. In thick weather, when landmarks cannot be seen, the navigator of a transoceanic vessel can tell when he is

approaching the coast by the rapidly shallowing depths. In coastwise navigation, during thick weather, a series of soundings is taken, spaced at frequent intervals. These are plotted, to the same scale as the sailing chart, on a piece of transparent paper which is then moved about on the chart along the ship's course until the soundings taken agree with the depths shown on the chart, and thus the position of the vessel becomes determined.

The fact that a layer of water veils the bottom of the sea from view makes it necessary to have recourse to the laborious and expensive method of sounding in order that a knowledge of its topography may be gained. Even more difficult does this intervening layer of water make the study of the nature of the material composing the sea bottom, for we are effectually prevented from examining anything but the topmost layers. On land such simple tools as a pick and spade and augur permit us to examine readily the earth's crust for considerable depths. In the sea, however, even with elaborate apparatus we can at best reach down a foot or two below the topmost layer of the bottom.

That the material on the sea bottom differed at different places was known to the ancients. Herodotus relates that the mariners of his time made practical use of this fact. The land along the coast of Egypt is low and therefore not visible from any considerable distance offshore. But when the sounding lead, from a depth of about ten fathoms, brought up Nile mud, the mariner knew that the coast of Egypt would be reached within a day. It was early realized, too, that of the material carried into the sea by continental rivers or by wave action, the coarser would be deposited close to the coast and the finer farther out.

But there was no knowledge of the matter actually forming the bottom out in the open sea. Not until the first successful deep-sea sounding was made by Captain Phipps in 1773, was a sample of the bottom from the depths of the

sea examined. When the sounding lead was brought up from the bottom at a depth of 683 fathoms, there was found adhering to the tallow, with which the lead was armed, some fine blue mud. Generally the sounding lead is hollowed out at the bottom and the hollow filled, or as it is more usually expressed, armed with tallow or soap. On striking bottom a fine layer of the material will adhere to the tallow and in this way a sample is secured. For great depths this is not always a successful method, for in its long journey upward the sample may be washed off the tallow.

With improvements in the apparatus for deep-sea sounding came also improvements in bottom samplers. In one form the sinker attached to the sounding lead drove a pair of jaws into the bottom which on being pulled up would close on the sample. In another form the sinker is fitted around a tube which plunges into the bottom and thus brings up a sample. In connection with the laying of the telegraph cables it became important to know the nature of the bottom and many samples were secured by cable-laying ships. Various exploring expeditions likewise gathered bottom samples, some of these expeditions making use of a dredge which was towed along the bottom and thus brought up material of larger dimensions than is possible with the usual plunging tube.

The famous *Challenger* expedition, which between the years 1872 and 1876 circumnavigated the globe and traversed the oceans in various directions, gathered a large number of bottom samples. And it was in connection with the discussion of these samples that the first comprehensive account of the deposits of the sea bottom appeared. This account was written by Sir John Murray and Professor Alphonse Renard and was published in 1891 as one of the *Challenger* reports under the title, *Deep Sea Deposits.*

Into the technical classification of the various deposits by Murray and Renard we need not enter. As a primary

classification we may recognize as shallow-water deposits those extending from the shore to the 100-fathom line, and as deep-sea deposits those extending beyond the 100-fathom line. The shallow-water deposits are composed of material derived from the land, this material being brought into the sea either as a result of wave action or through the agency of rivers. Boulders, gravel, sand and sometimes mud constitute the shallow-water deposits, the material at any particular place depending on the character of the adjoining coast. As a rule, the coarser material is found near the coast, the texture becoming finer with increasing distance from shore. In all, the shallow-water deposits cover about ten per cent of the bottom of the sea.

In the sea beyond the 100-fathom line, the deposits are principally red clay, various oozes and several different kinds of mud. Where the bottom slopes steeply from the shore, that is, where the 100-fathom line lies near the land, gravel and sand may occur as deep-sea deposits, but these are relatively rare. Of the sea bottom beyond the 100-fathom line, it is estimated that 17 per cent is covered by mud, 40 per cent by red clay and 43 per cent by oozes of various kinds.

The muds, as a general rule, may be said to lie on the continental slopes and shallower parts of the sea within the vicinity of the 100-fathom line. They are derived from the land, being the finer particles carried in suspension from the disintegration of the shore material or from the matter carried seawards by rivers. They are classified according to color and in accordance also with origin. Thus, there are blue, red, green, volcanic and coral muds. The color in each case is due to the presence of certain compounds resulting from chemical action. The volcanic and coral muds are derived respectively from volcanic islands and from coral reefs and coral islands.

Red clay is the characteristic deposit of the deeper parts

of the bottom of the sea, being the most widely distributed and found in all the oceans. Chemically, it is composed mainly of hydrated aluminum silicate, and it is derived from the decomposition of pumice and other volcanic minerals and from interstellar dust. Its red color is due to the presence of oxides of iron and manganese which result from the decomposition of volcanic minerals.

Various oozes constitute the deposits on the remainder of the bottom of the deep sea. These are formed mainly from the calcareous and silicious remains of plants and animals which lived in the waters under which the deposits are found. Various oozes are recognized, the most widespread being globigerina ooze, which covers an area of about forty million square miles of the sea bottom. This deposit consists mainly of the shells of Foraminifera which live in the surface waters. Diatom ooze is next in abundance, and as its name indicates is formed from the silicious remains of diatoms, microscopic plants which occur in enormous quantities in cold surface waters.

CHAPTER X

THE LEVEL OF THE SEA

THAT the undisturbed surface of a body of water, large or small, constitutes a level surface is almost axiomatic. As a matter of course, we reckon heights on land and depths in the sea from the level of the sea by expressing these as so many feet or miles above or below sea level. To be sure, the surface of the sea is at all times disturbed by wind and wave and tide. But we feel instinctively that if by one means or another the effects of these disturbing agencies are eliminated, we arrive at the true level of the sea, a level surface.

In connection with a number of problems, of both practical and scientific character, it becomes necessary to determine accurately this level of the sea, or mean sea level as it is frequently called. When this is attempted the fact develops that it is far from a simple matter, for sea level determined at one time is found to differ from that determined at the same place at another time. After eliminating the disturbing effects of tides and waves, sea level is found to vary from day to day, from month to month and from year to year.

The disturbing effects of waves may be eliminated in various ways. By connecting a well with the sea by means of a pipe, the inlet of which is placed some distance below the surface of the sea, the water in the well will at all times be at the same level as that of the sea, but it will at the same time be free from waves. A simpler method is to choose some sheltered spot in a harbor, which may be done

at many places. As regards the effects of the rise and fall of the tide, it is evident that since this rise and fall has a period of about twelve and a half hours, the disturbing effect of the tide on sea level may be largely eliminated by measuring the height of the surface of the sea at frequent intervals during a half day and averaging these heights. A better elimination will be effected if the height of the sea is measured at regular intervals during an entire day, and these heights averaged.

Now suppose that in some harbor like New York we fix in a vertical position, against the face of a wharf, a board on which a scale of feet and tenths of feet has been painted. Then, if during the whole day at regular intervals, say every ten minutes, we read the height of the water on this scale, the level of the sea for that day will be derived by averaging our ten-minute readings of the height of the water. However, instead of making our readings of the height of the water "by hand," it will be more advantageous to get this done by some instrument. Various instruments may be used which will automatically record the height of the water at regular intervals; or better yet, we may use an instrument which draws a continuous curve of the height of the water throughout the day. From such a curve it is a simple matter to get the height of the water at frequent intervals. Averaging these heights for a day gives the height of sea level for that day.

In Figure 7 are shown in diagrammatic form the relative heights of sea level in New York Harbor for each day of the month of February, 1919, these heights being indicated by the open circles of the figure. A glance is sufficient to show that sea level varied from day to day, sometimes by as much as a foot or more. Obviously, such changes are to be ascribed, in large part at least, to variations in wind and weather. It is a matter of common knowledge that a wind blowing toward the shore tends to raise the level of

the sea along the shore, while a wind blowing from the shore tends to lower it.

On the North Atlantic coast of the United States, February is generally a month with considerable variation in wind and weather. And it might therefore be argued that, if some summer month had been chosen, sea level would show no variation from day to day. Examining, therefore, the height of sea level during a typical summer month we find that while the level of the sea from day to day does not vary as much as in winter, it nevertheless does vary. For example, in the month of June for the same year as

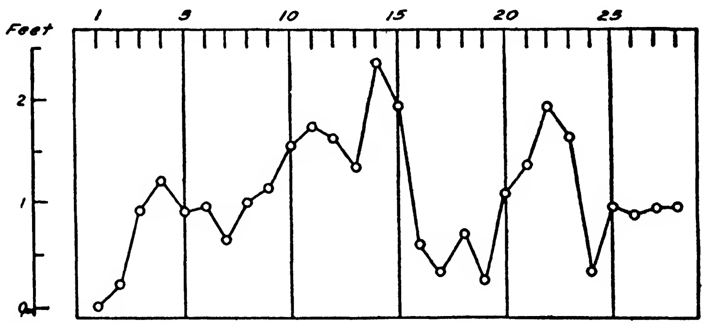

FIG. 7.—DAILY SEA LEVEL, NEW YORK HARBOR, FEBRUARY, 1919

shown in Figure 7 the difference in the height of sea level for two successive days was as much as half a foot.

The wind is not the only agency which may cause differences in the level of the sea from day to day. Variations in barometric pressure likewise bring about fluctuations in sea level. Indeed, we may regard any arm of the sea as constituting a huge inverted water barometer. When the atmospheric pressure over this arm of the sea rises, the level of the water will be lowered, and when the pressure decreases, the level of the water will rise.

The relation between changes in barometric pressure and the resultant changes in sea level may be easily derived

as follows. The barometric pressure is measured in inches (or millimeters) of mercury. And since mercury is thirteen times as heavy as sea water, it follows that a change in barometric pressure of one inch should be reflected by an inverse change of thirteen inches in the level of the sea. Or, approximately, we may put it that the change in sea level in feet should be inversely as the change in barometric pressure in inches.

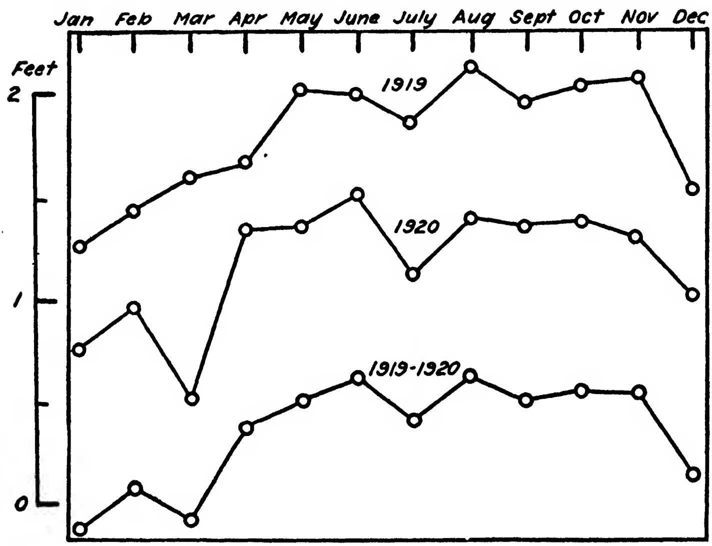

FIG. 8.—MONTHLY SEA LEVEL, NEW YORK HARBOR, 1919-1920

From day to day wind and weather may vary widely and thus give rise to relatively wide variations in sea level from day to day. But within a month such variations obviously tend to balance out. Suppose, then, we average the varying height of the sea over periods of a month and examine the results. Taking New York Harbor again and using the observations for the years 1919 and 1920, the results are shown in diagrammatic form in Figure 8.

The upper curve gives the height of sea level in New York Harbor for each month of the year 1919, while the middle curve gives it for the corresponding months of 1920. It appears at once that the level of the sea is not constant from month to month; but, as was to be expected, the variation is not nearly so large as that from day to day. For the two years shown in Figure 8, sea level from one month to the next varied from less than a tenth of a foot to as much as three-quarters of a foot. And during this two-year period sea level for the month of August, 1919, was exactly one foot higher than for the month of March, 1920.

At first glance the heights of sea level for the different months of 1919 and 1920, represented by the upper two curves of Figure 8, appear to vary in haphazard fashion. A closer examination, however, reveals unmistakably the presence of a large element of periodicity. For each of these years sea level appears to be low in the winter months and high in the summer months. This is brought out clearly in the lower curve of Figure 8, which is designed to illustrate the monthly variation in sea level in New York Harbor as averaged for the two years under discussion, 1919 and 1920.

Further study completely confirms the existence of a seasonal variation in sea level not only in New York Harbor, but the world over. From one year to another this seasonal variation will obviously differ somewhat, since wind and weather do not repeat themselves exactly from year to year. But if at any one place we average the corresponding monthly heights of sea level for a number of years, haphazard or nonperiodic variations will be eliminated and the seasonal variation will appear in its periodic form. The seasonal variations in wind and weather being different at different places, it is to be expected that the seasonal variation in sea level will likewise vary from place

to place. This is borne out by observations, and is illustrated in Figure 9 for the harbors of Boston, New York, and Charleston.

The horizontal line associated with each curve in Figure 9 represents the mean level of the sea at each of the stations as determined from a number of years of observations. The open circles give the heights of monthly sea level relative to mean sea level. Each curve shows distinc-

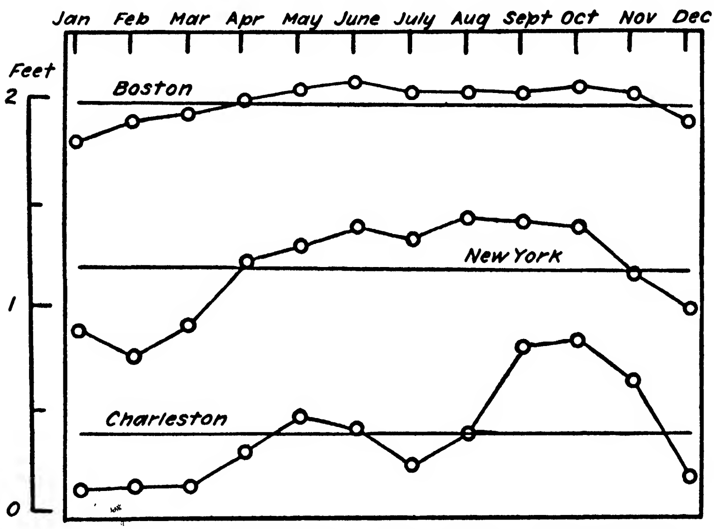

FIG. 9.—SEASONAL VARIATION IN SEA LEVEL, UNITED STATES ATLANTIC COAST

tive features as regards both the range of the seasonal variation and also its phase. This means, in other words, that at each place the seasonal variation in sea level has definite local characteristics. It will be noted, however, that along the Atlantic coast of the United States the range in the seasonal variation of sea level shows wider differences than does the phase. Indeed, from Boston to Charleston the phase may be said to be very much the same. All along

this coast the level of the sea is, on the average, below its mean height in the winter and early spring, and above its mean height in the autumn. Characteristic, too, is the slight fall during July, which becomes more accentuated in going from north to south.

For comparison with the seasonal variation of sea level

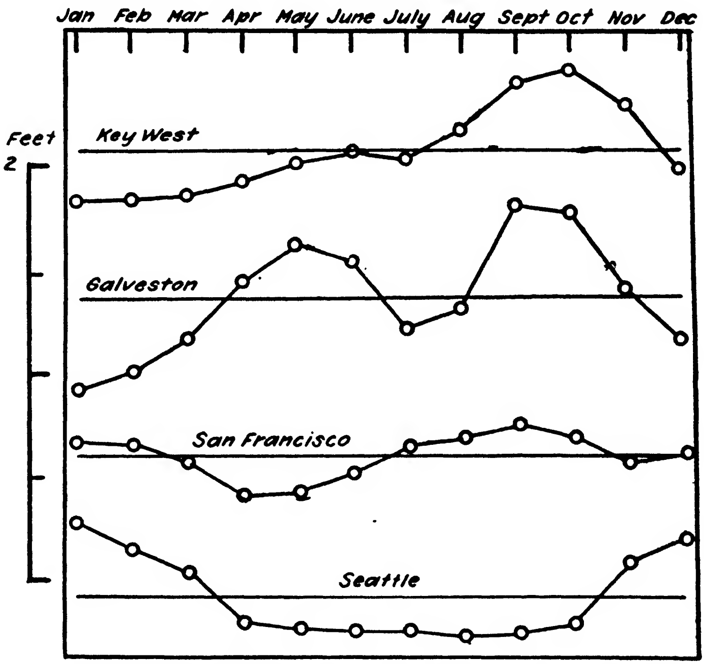

FIG. 10.—SEASONAL VARIATION IN SEA LEVEL, UNITED STATES GULF AND PACIFIC COASTS

in the harbors on the Atlantic coast of the United States illustrated in Figure 9, there are shown the curves of seasonal variation at several ports on the Gulf and Pacific coasts in Figure 10. For the Gulf of Mexico the curves for Key West, Florida, and Galveston, Texas, show that the seasonal variation of sea level is somewhat similar to

that along the Atlantic coast. On the Pacific coast, however, the variation is totally different. Moreover, the curve for San Francisco, California, is radically different from that for Seattle, Washington.

It is to be observed that the places chosen for illustrating the existence of a seasonal variation in the height of sea level were all situated along continental coasts. The question may therefore arise whether sea level away from the continents exhibits a seasonal variation. Out in the open

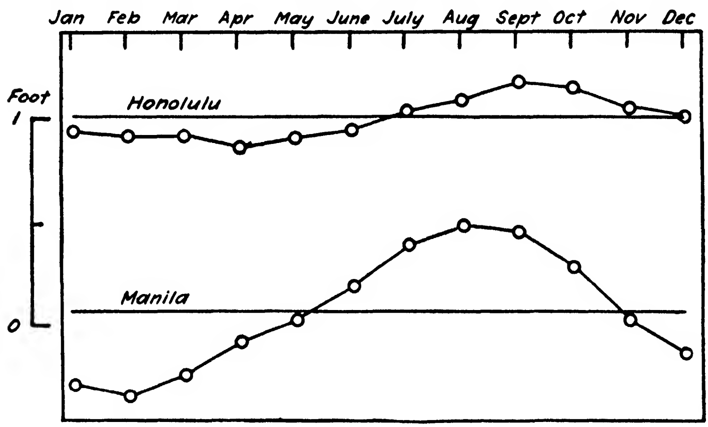

FIG. 11.—SEASONAL VARIATION IN SEA LEVEL, HONOLULU AND MANILA

sea the difficulties involved in making the necessary observations are so great that to the present time there are no such observations on which to base an answer to the question. But observations can be made on the shores of oceanic islands. In Figure 11 are shown the curves of seasonal variation in height of sea level at Honolulu in the Hawaiian Islands, and at Manila in the Philippine Islands. These curves show at once that on the shores of oceanic islands the height of sea level varies regularly throughout the year, and we are therefore justified in concluding that

out in the open sea, too, the level of the sea varies with the seasons.

Summarizing our conclusions thus far with regard to the level of the sea, we may say that sea level varies from day to day and from month to month. The change in sea level from one day to the next is almost wholly of a nonperiodic character, depending on prevailing weather conditions. The change in sea level from month to month, however, is partly periodic and partly nonperiodic. Furthermore, the periodic variation at any particular place exhibits features of distinctive local character.

Now if we average the height of sea level at any one place over the period of a year, it is obvious that the periodic seasonal variation will be eliminated. Within a year, too, the nonperiodic fluctuations in sea level tend to balance out. We might, therefore, be led to conclude that sea level derived from a year of observations will so closely approximate mean sea level that from one year to the next there will be no variation. Let us test this conclusion by examining the results of observations.

In Figure 12 are plotted the yearly values of the height of sea level in New York Harbor and in San Francisco Bay for the twenty-eight-year period from 1898 to 1925. For each year sea level was determined by averaging the height of the surface of the sea as measured at the beginning of every hour. In other words, each of the yearly heights shown in Figure 12 is the average of more than eight thousand hourly heights of the level of the sea. The horizontal line drawn through each of the two curves represents the mean sea level at each of the places, as derived from the twenty-eight years of observations.

That sea level varies from year to year is evident at once from Figure 12. But that this variation is relatively small is likewise evident from the fact that the scale giving the heights in the figure must make use of divisions as

small as tenths of a foot. From one year to the next the change in sea level is generally less than a tenth of a foot, though at times it may be as much as a quarter of a foot or even more, as exemplified by the variation between the years 1900 and 1901 in New York Harbor and between 1913 and 1914 in San Francisco Bay. Figure 12 also brings out the fact that the variation from year to year is not progressive. That is, the sea level of one year is

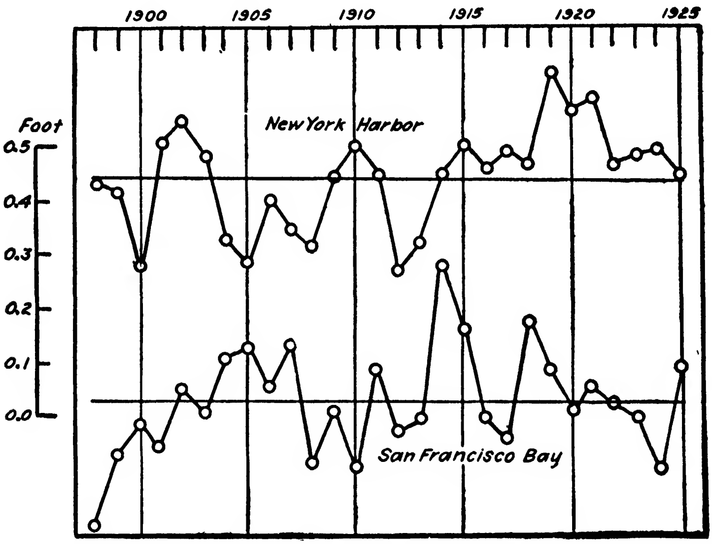

FIG. 12.—YEARLY SEA LEVEL, NEW YORK AND SAN FRANCISCO

not always lower than the preceding year, nor is it always higher. For several years it may go down and then for the following period of several years, it will rise.

A comparison of the two curves of Figure 12 shows that no simple relation exists between the variation in yearly sea level at New York and that at San Francisco. But if we compare New York with some other port on the North Atlantic coast of America, or San Francisco with some

other port on the North Pacific coast, we find that, as regards yearly sea level, they behave very much alike. In fact, a detailed study of this phase of the question on the Atlantic coast of the United States brings out clearly that, if for any one year sea level is high at one point on the coast, it is high all along the coast; and similarly for a year of low sea level. For the whole of the Pacific coast of the United States a similar state of affairs has likewise been found to obtain. This feature, we shall see later, is of considerable importance in the determination of mean sea level.

A number of problems arise from the fact that sea level varies from year to year. To begin with, we are confronted by the questions of what constitutes mean sea level and how long a period of observations is necessary to determine it. Since the change in sea level from year to year is not progressive, it is obvious that the longer the period of observations, the closer the approximation to mean sea level. From considerations based on the theory of the tides, a period of nineteen years is taken as constituting a full tidal cycle, for during this period the more important of the tidal variations will have gone through complete cycles. Hence sea level derived from nineteen years of observations may be taken as giving accurately the mean sea level at any place.

Nineteen years is a relatively long period of time. Cannot the period of observations necessary for securing an accurate determination of mean sea level be shortened? Examining the curves of Figure 12, rough periodicities become apparent. Thus, in the change of sea level in New York Harbor there appears a period of approximately nine years, as the peaks for the years 1902, 1910 and 1919 bring out. A like period is also evidenced to some degree by the curve for San Francisco. There appears, furthermore, a variation with a period of something like four or five years

—clearly shown in the curve for New York Harbor and somewhat less clearly for San Francisco Bay.

Whether these are true periodicities, and if so, what they are due to, are matters about which little is at the present time known. But, taken in connection with the fact that the change in sea level from year to year is not progressive, these periodicities make possible a determination of mean sea level over periods much less than nineteen years. If we average the height of sea level over periods of nine years we get a very close determination of mean sea level, and even four years give a result sufficiently accurate for most purposes.

Advantage may also be taken of the fact that all along any coast the change in sea level during a given period is much the same. Thus, if it is required to determine mean sea level at any point on the Atlantic coast, a year of observations at that point is compared with simultaneous observations at some place like New York where a long series of observations has already been secured. By means of this comparison, the mean sea level at the point desired may be derived with a good deal of precision. Indeed, by this method of comparison we can, from a month of observations, determine mean sea level within a tenth of a foot, whereas the result of the observations uncorrected by means of such comparison might be as much as half a foot or more in error.

In connection with the question of the stability of the coast the accurate determination of mean sea level assumes great importance. For such determinations furnish perhaps the only data of a quantitative nature in studying whether a given coast is rising, sinking or remaining stationary. If it be assumed, as is sometimes done, that sea level determined from one year of observations gives a close approximation to mean sea level, erroneous conclusions with regard to the coast are bound to result.

As an example, suppose the alleged gradual subsidence of the coast of New Jersey were being studied and that the coast at Atlantic City were chosen, the study beginning in 1912. Throughout that year the height of the sea was recorded automatically, and sea level was determined by averaging the heights at the beginning of each hour. This average height of sea level was then very carefully related to some fixed point on the shore.

Seven years later, in 1919, the observations were repeated with the same care as before. Now, however, the point on the coast which in 1912 was exactly at sea level, in 1919 was found to be 0.36 foot below sea level. In other words, in the seven years from 1912 to 1919 there was an apparent sinking of the coast of more than a third of a foot or at the rate of five feet a century.

But this sinking is only apparent; for, as we have seen, sea level varies from year to year, and as determined from one year of observations may differ several tenths of a foot from mean sea level. Turning back to Figure 12, it is seen that 1912 was a year of low sea level on the Atlantic coast of the United States, while 1919 was a year of high sea level—being in the former year at New York 0.17 foot below its mean value and in the latter year 0.20 foot above its mean value. If now we correct our yearly values of sea level at Atlantic City to a mean value we find that instead of a difference of 0.36 foot during the seven years, the difference is only one hundredth of a foot. In other words, no change in the relation of land to sea took place during this period, for a difference of a hundredth of a foot is obviously too small to be of significance in this connection.

Long series of sea level observations furnish the data for determining the relative elevations of land to sea. If these observations give, superimposed on the fluctuations from year to year, a continually rising sea level, then, ob-

viously, either the coast is sinking or the level of the sea is rising. But to determine this with any degree of precision long series of observations are necessary, in order that the fluctuations of sea level from year to year may be eliminated. Furthermore, long series are necessary to eliminate any periodic cycles such as the four- and nine-year cycles of which some evidence was found. It is possible, too, that variations of still longer period exist in the change of sea level—perhaps one with a period of something like thirty-five years corresponding to the so-called Brückner cycle in the weather.

The question of what brings about the fluctuations in sea level we have been discussing opens up a subject with many ramifications. Undoubtedly, these fluctuations are due to the variations in a large number of factors, among which may be mentioned barometric pressure, direction and velocity of wind, rainfall and evaporation, temperature and density of sea water, and the velocity and direction of non-tidal currents. The larger fluctuations in sea level that occur from day to day show a very close correlation with the variations in wind and in barometric pressure, and it appears reasonable to assume that the variations of longer period likewise are to be ascribed to changes in wind and weather.

It is to be observed, however, that in ascribing the variations in sea level to effects of wind and weather it is tacitly assumed that the mean level of the sea remains fixed. But may not this mean level itself be changing? In answer to this question it may be noted that such a change in the absolute level of the sea may arise from a change in the volume of the ocean basins or from the change in the volume of the ocean waters. As to the causes that are adequate to bring about such changes a number may be mentioned: earth movements which bring about changes in the dimensions of the ocean basins; addition of water

through volcanic action or subtraction of water through chemical binding during the alteration of rocks; decrease of water through increased glaciation on land or increase of water through decreased glaciation.

That changes in the absolute height of sea level have taken place during geologic time by reason of the operation of the causes enumerated above is unquestioned. As regards any such changes which may be taking place now, it is obvious that, in view of the enormous volume of the ocean waters, changes in the absolute height of sea level must be extremely small—so small, in fact, as to escape detection except by careful observations over periods of time measured in centuries.

CHAPTER XI

THE SURFACE WATERS

The importance of water in the scheme of nature was sensed even in ancient times. To Thales, the Greek philosopher who lived about 600 B.C., is credited the saying that water is the origin of all things. Later, when Aristotle attempted to reduce the enormously complex manifestations of the physical world to basic elements, he found these in water, air, earth, and fire. And with the growth of systematized knowledge, which we designate by the general name of science, the rôle played by water has been recognized as even more far-reaching.

The sea constitutes the great reservoir of water of our planet. As we found in our consideration of the depths of the sea, the quantity of water contained in this great reservoir is about 329 million cubic miles—sufficient, if all the inequalities of the earth's crust were smoothed out, to cover the entire earth with a layer one and one-half miles deep. The characteristics of this enormous body of water must, obviously, be of profound influence in the make-up of our physical environment. These characteristics of the waters of the sea we will now consider, taking up first the surface waters.

Sea water is unsuitable for drinking, having a characteristically salty taste, imparted to it by various salts that are carried in solution. Chemical analysis proves that a thousand pounds of sea water contains, on the average, 35 pounds of solid matter dissolved in it. Of these 35 pounds, common salt or sodium chloride constitutes 27.21 pounds,

magnesium chloride 3.81 pounds, magnesium sulphate 1.66 pounds, calcium sulphate 1.26 pounds, potassium sulphate 0.86 pound. The remainder, 0.2 pound, is composed principally of calcium carbonate and magnesium bromide and traces of other compounds. On a percentage basis this means that of the salts dissolved in sea water, sodium chloride constitutes 77.8 per cent, magnesium chloride 10.9 per cent, magnesium sulphate 4.7 per cent, calcium sulphate 3.6 per cent, potassium sulphate 2.5 per cent, while the remaining half of one per cent is made up by calcium carbonate, magnesium bromide and other compounds.

Of the matter carried in solution by sea water the principal constituent is thus sodium chloride or common salt, constituting more than three-quarters of the dissolved matter. Not only is salt a necessary condiment in the food of man, but it enters also as an important factor in many chemical industries and in the manufacture of such diverse articles as brick, pottery, paper, soap, textiles, oil, and ice. Our very language bears testimony to the significance of salt, for that very important word "salary" has as its root *sal*, the Latin word for salt, its meaning being derived from the ancient Roman practice of giving soldiers part of their pay for the purpose of buying salt.

Whatever the present source of salt, whether from mines or wells or sea water, the ultimate source is to be found in the sea. For all salt deposits are but the remains of dried-up seas. From prehistoric times sea water has been the primary source of salt. Even to-day there are many regions where sea water is evaporated to furnish the salt that is used.

Now it is an interesting fact that, while the total amount of salts contained in a given volume of sea water varies in different places, the percentage of the various salts is everywhere the same. For example, in certain parts of the Red Sea there are in a thousand pounds of water 40 pounds

of salts while in the Baltic Sea a thousand pounds of water contains but 8 pounds of salts in solution. Nevertheless, the relative proportions of the various salts in each of these waters is the same.

The fact that the different salts dissolved in sea water are always present in the same proportion means also that the various elements composing these salts likewise bear a constant ratio to each other. Thus, chlorine constitutes 55.3 per cent of the matter dissolved in sea water and sodium 30.6 per cent, no matter what the total amount of the salts dissolved may be. This fact of the constancy of composition of dissolved salts in the sea is made use of in determining the salinity of a given sample of water. For it is a relatively simple matter to determine the amount of chlorine in the sample. And since chlorine constitutes 55.3 per cent of the dissolved matter we need only multiply the amount of chlorine found by the reciprocal of 55.3 per cent, which is 1.81, to determine the total amount of dissolved matter in the given sample.

At first thought, the simplest method for determining the amount of matter dissolved in a given volume of sea water would appear to be the evaporation of the water, and the drying and weighing of the residue. The objection to this method is not only that it is time-consuming, but also that it is not accurate; for in the evaporation of the water certain of the dissolved constituents are volatilized and driven off with the water.

Several different methods have been found serviceable in determining the salinity of sea water. The so-called titration method is based on the constancy of composition of the dissolved matter, and determines the amount of chlorine present in a given sample of sea water. The total salts are then determined, as explained previously, by multiplying the amount of chlorine found by 1.81. In practice, a definite quantity of sea water is taken and a sufficient

amount of a solution of silver nitrate is added to precipitate all the chlorine as silver chloride. Each unit quantity of the silver nitrate solution corresponds to a definite amount of chlorine, so that the amount of silver nitrate solution required to precipitate all the chlorine in the sample gives immediately the amount of chlorine present.

Another method makes use of the hydrometer by means of which the density of the given sample of sea water is determined. The density of sea water varies with the amount of salts in solution, and tables have been prepared which give the salinity corresponding to various densities. The hydrometer is immersed in the sample of the sea water and its density read off. From the tables the salinity corresponding to this density is then determined. In this connection it is to be remembered that the density of water varies with the temperature, so that in the use of this method the temperature of the water sample must be taken, and the density reduced to a standard temperature before the salinity can be determined.

Other methods make use of various physical characteristics of water. Thus, certain optical properties of water vary with the salinity, and a method for determining the salinity of sea water based on this fact has been developed. A recent method makes use of the fact that the salts dissolved in sea water make it a good conductor of electricity, the conductivity varying with the salinity. By measuring the conductivity of a given sample of sea water, the salinity corresponding to it becomes determined. This method is especially promising, since it is suitable for use aboard a vessel and since it lends itself to the construction of an automatic recording instrument which will give a continuous curve of the salinity of the water through which a ship is passing.

Sufficient observations of the surface waters of the various oceans and seas have been made to give us a general

knowledge of the salinity in various parts of the world. But before we take up the distribution of salinity, it will be of advantage to digress for a moment to a consideration of the scale on which salinity is measured. It has now become the accepted custom throughout the world to measure it in terms of the dissolved salts per thousand parts of water. This means that the smallest integral unit corresponds to one tenth of one per cent. Thus, sea water with a salinity of 35.7 means that in a given weight of that water 0.0357 part, or 3.57 per cent, is made up by the salts carried in solution.

It is to be expected that the salinity will vary in different parts of the sea. In coastal waters and over the shallower parts of the continental shelf the fresh water carried down from the land by rivers tends to make the surface layers less saline than the surface waters of the open sea. In regions where there is a great deal of evaporation and but little rainfall, it is obvious that the water will be more saline than in regions having less evaporation or more rainfall. The great wind and current systems likewise tend to separate off regions of different salinities.

In the open sea the salinity varies, in general, with latitude. The waters in the equatorial regions have a salinity of about 35. Bordering this water in both hemispheres is a belt having a higher salinity, about 36. In the northern hemisphere this belt of high salinity lies roughly between the twentieth and fortieth parallels of latitude, while in the southern hemisphere it lies between the tenth and thirtieth parallels. Beyond these belts of high salinity the surface waters of the sea become gradually less saline, attaining in latitude 60° a salinity of about 31 in the northern hemisphere and about 33 in the southern hemisphere.

In this generalized view of the distribution of salinity in the surface waters we see the effects of meteorological conditions. In the equatorial regions we have high tempera-

tures, but relatively little wind and excessive rainfall. This gives the surface waters in these regions a moderate salinity. On both sides of this equatorial belt are regions still of high temperature, but here the evaporating effect of the high temperature is increased by the strong and constant trade winds. Furthermore, the rainfall is less than in the equatorial regions. Hence we find here belts of high salinity. The gradual decrease in salinity in higher latitudes is obviously due in part to the decreasing temperatures. It is aided also by the influx of fresh water resulting from the melting of ice, which tends to remain on the surface because of its low density.

Taking the individual oceans, we find in the North Atlantic a region of high salinity within the Sargasso Sea, in the central part of which the salinity is as high as 38. In the South Atlantic there is a similar region of high salinity lying off the coast of Brazil. No large area of the surface waters in the North Pacific has a salinity greater than 36, but in the South Pacific there is such an area off the coast of Peru with a salinity of 36.5. In the Indian Ocean a considerable area, extending southward from the Persian Gulf to the equator, has a salinity of 36 and another area west of Australia has a like salinity.

Within the dependent seas, too, there are regions of varying salinity; but for our purposes it is not necessary to enter into a detailed consideration of this feature. Taken as a whole, the dependent seas exhibit greater variety in the salinity of the surface waters than do the oceans; for being smaller in area the factors that influence salinity—temperature, rainfall, evaporation, winds, currents, and inflow of river water—have greater potency in impressing their local effects. As seas of high salinity may be mentioned the Mediterranean, the surface waters of which have a salinity of about 39; the Gulf of Mexico and the Caribbean Sea with salinities of about 36; the Persian Gulf with a salinity

of about 37; and the Red Sea with the highest salinity of all, about 40. The high salinities of the surface waters of these seas obviously find explanation in the fact that they lie within regions of high temperature, where evaporation is greater than the addition of fresh water by rivers and rainfall.

Seas lying in high latitudes may be expected to show low salinity in the surface waters because of low temperatures and little evaporation, and also because of the presence of fresh water from melting ice which, because of its low density, tends to remain on the surface. In Bering Sea we find the surface waters having a salinity of between 31 and 32 and in the Arctic Sea a salinity less than 30. In temperate zones the salinity depends largely on the relative volume of fresh water brought in by rivers. Thus, in the North Sea, the relatively large area and free communication with the open sea makes it possible for the surface waters to have a salinity of between 34 and 35. In the more nearly landlocked and smaller Baltic Sea, the river waters exert so profound an influence as to give the surface waters a salinity less than 10.

Is the salinity of the surface waters of the sea subject to variations? In the smaller dependent seas, in which the influx of the fresh water that drains off from the land is a factor of primary importance in the salinity of the surface waters, it is obvious that variations in salinity must occur. For during periods of maximum run-off from the land, the salinity of the surface waters will be less than usual, while during periods of minimum run-off the salinity will be greater. In the smaller seas, too, heavy storms may bring about conditions differing considerably from those normally prevailing, either by a more thorough mixing of the surface with the subsurface waters, or by bringing in an unusually large amount of water from the open sea.

In the open sea variations in salinity of the surface

waters may occur, generally as a result of variations in the flow of currents which bring waters from one region into another. As a rule, however, such variations are small, and affect but restricted areas.

We may conclude our survey of the salinity of the surface waters with a consideration of its distribution in relation to latitude. On the basis of the material at hand, the German oceanographer, Dr. Otto Krümmel, published in

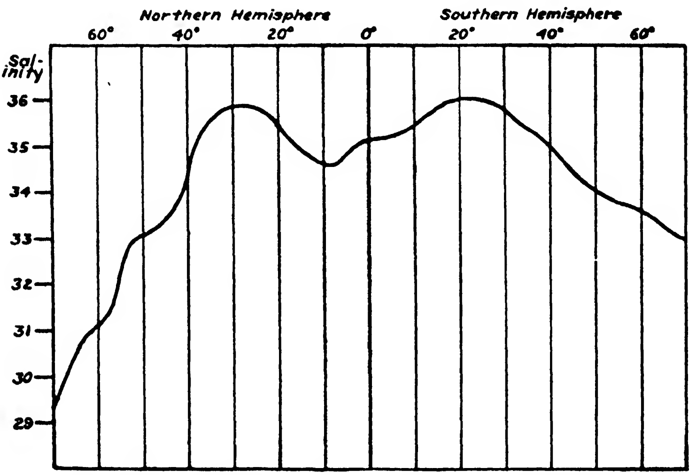

FIG. 13.—VARIATION OF SALINITY WITH LATITUDE (AFTER KRÜMMEL)

his *Handbuch der Ozeanographie* a table giving the salinity of the surface waters of the sea as a whole for each five-degree zone of latitude. And parenthetically it may be remarked that Krümmel's *Handbuch* of two volumes with some twelve hundred closely printed pages still constitutes the standard treatise on oceanography, although published about twenty years ago. On the basis of the salinities given in Krümmel's table Figure 13 has been drawn.

The curve of Figure 13 gives us a comprehensive view

of the relation of salinity to latitude for the sea as a whole. In the higher latitudes—from 70° to the poles—the salinity is not sufficiently well known to justify inclusion in our diagram. Hence, the curve covers the sea between the latitudes of 70° N. and 70° S. The diagram brings out clearly that, in general, the salinity varies inversely as the latitude, being high in low latitudes and low in high latitudes. However, the maximum salinity occurs, not at the equator, but in two belts lying about 25° or, roughly, fifteen hundred miles either side of the equator. This feature in the distribution of salinity of the surface waters was discussed on page 134 and was found to be due to the effects of a number of meteorological factors.

Figure 13 also brings to light the fact that the sea as a whole is more saline in the southern than in the northern hemisphere, the salinity in the former being approximately 35 and in the latter 34. This difference is a reflection of differences of meteorological and climatological factors in the two hemispheres. It is a reflection, too, of the fact that the northern hemisphere contains the larger part of the earth's surface above sea level and a larger area of dependent seas.

The question of the origin of the salts in the sea and the related question as to whether the sea as a whole is changing in salinity, it will be better to defer until these matters are discussed in the following chapter in connection with the waters of the depths of the sea. Now it will be of advantage to consider a feature of the surface waters which obviously is not unrelated to salinity, namely, temperature.

The determination of the temperature of the surface waters of the sea is a much simpler matter than the determination of the salinity; for wherever a vessel may be, all that is needed is to dip up some water from the surface in any kind of a receptacle, and measure the temperature

of this water with a thermometer. To be sure, in order to secure the accuracy desired by the professional oceanographer certain precautions must be taken, but these are merely technical details.

Modern oceanographic research makes use, whenever possible, of automatic recording instruments. Such instruments for recording automatically and continuously the temperature of the water through which a vessel is passing have been developed under the name of thermographs. These instruments accurately record the temperature of the water in the form of a continuous curve from which the temperature at any desired time may be readily and easily determined.

Temperature is a matter which concerns us in our everyday affairs, so that we are all familiar with the thermometer and with the temperature scale. In technical and scientific work the centigrade thermometer scale is used throughout the world. On this scale 0° is the freezing point of water and 100° the boiling point. In everyday life in English-speaking countries, however, it is the Fahrenheit temperature scale that is used, with the freezing point of water marked 32° and its boiling point 212°. Since most of us are accustomed to this latter scale, temperatures given in this volume will be in degrees Fahrenheit. To convert degrees Fahrenheit into degrees centigrade it is only necessary to subtract 32 and multiply by $5/9$.

We are familiar with the fact that the temperature of the air is a highly variable matter. To say, for example, that a temperature of 60° was observed at a certain place gives us but little information, for it makes all the difference in the world whether this temperature was observed in winter or in summer, at night or during the day. Furthermore, we want to know whether this temperature is the usual temperature for the particular time. In other words, we recognize that the temperature at any place is subject

to a daily variation, a seasonal variation, and also to accidental variations, or, more accurately, nonperiodic variations.

Since the temperature of both the air and the surface waters is due to the heat received from the sun, we may look for temperature variations in the ocean waters similar to those discussed in the preceding paragraph for the air. That is, from general considerations we may expect to find the temperature of the surface waters to exhibit a daily variation, an annual variation, and also nonperiodic variations. And, as a matter of fact, observations have shown this to be the case.

In the daily variation of the temperature of the air, it is not at all uncommon, especially in inland regions, to have a difference of from twenty to thirty degrees, or even more, as between day and night. No such daily variation takes place in the temperature of the sea. From observations made in the various oceans, the difference in temperature of the surface waters between day and night is barely one degree. And this more equable temperature condition of the ocean waters finds reflection in a more equable temperature of the air over the sea. Instead of a daily variation of as much as twenty degrees or more, which characterizes the air in many inland regions, the daily variation in the temperature of the air over the oceans is but several degrees.

Now the average temperature of the surface waters of the sea at any place is practically the same as the average temperature of the air at that place. And since the daily temperature variation is less for the water than for the air, it follows that at night the surface of the sea is warmer than the air above it, while during the day it is cooler. In the different oceans the times of occurrence of the maximum and minimum temperatures of the day differ somewhat; but as a rule, the highest temperature comes

about two o'clock in the afternoon and the lowest about five o'clock in the morning.

With regard to the annual variation in temperature the sea is again more equable than the air. Even in temperate regions we are accustomed to a difference between summer and winter temperatures of 100 degrees or more. The year 1926 was not specially marked by extreme temperatures in the United States, yet during that year the difference between the highest and lowest temperatures experienced was 93 degrees in New York City; 97 degrees in the city of Washington; 103 degrees in Chicago; 116 degrees at Lincoln, Nebraska; and the hundred thousand and more inhabitants of the city of Duluth, Minnesota, took as a matter of course the difference of 122 degrees.

Such ranges in the annual variation of temperature as noted in the preceding paragraph are altogether foreign to the ocean waters. While the difference between the yearly highest and lowest temperatures of the surface of the sea varies somewhat in different places, over the greater part of the sea it amounts to, on the average, about 10 degrees. In certain areas, however, a range of as much as 40 degrees may be experienced, due to the fact that during the summer the surface waters in these areas come from tropical regions, while during the winter they come from polar regions.

It is to be expected that near the coast the surface waters will exhibit a greater range in annual variation of temperature than out in the open sea, reflecting the greater range of temperature in the air over the land. Observations prove this to be the case. This influence of the land explains, too, why the smaller dependent seas, as a general rule, exhibit greater annual ranges of temperature than the oceans. Thus, in the Mediterranean Sea the annual range in temperature is about 20 degrees, while in the Baltic Sea it is about 40 degrees.

The time of occurrence of the highest and lowest yearly temperatures obviously differs in the two hemispheres. In general, the surface waters of the sea in the northern hemisphere are coldest in February and warmest in August, while in the southern hemisphere the waters are coldest in August and warmest in February.

The daily and seasonal variations in temperature discussed above are of periodic character. In addition to these periodic variations the surface of the sea is subject to nonperiodic or accidental variations, arising from such causes as storms or variations in currents. But as was the case with the daily and seasonal changes, these nonperiodic variations are, as a rule, not nearly so great as the corresponding variations in air temperature.

As regards temperature, therefore, the sea is much less variable than the atmosphere. Both sea and atmosphere owe their temperatures to the heat received from the sun. Why, then, this great difference in response on the part of the two great seas, the sea of water and the sea of air?

The answer to this is found in the great capacity that water has for heat. Comparing water with mercury, for example, it is found that to raise by the same amount the temperature of equal volumes of the two liquids requires very nearly four hundred times as much heat for the water as for the mercury. And as regards air the difference in heat capacity is even more striking. For the heat necessary to raise, say, a cubic foot of water one degree is sufficient to raise the temperature of about three thousand cubic feet of air one degree.

In view of the fact that the temperature variations of the sea are much smaller than the variations in air temperature, it follows that the average or mean temperature of the surface waters at any place is more nearly a constant than is the case with the air temperature. And when we come to investigate the mean temperature of the surface

waters, we find latitude to be the determining factor. Taking the sea as a whole, the distribution of temperature of the surface waters is as shown in Figure 14.

A number of features with regard to the surface temperature of the sea are clearly brought out by Figure 14. The variation of temperature with latitude is evident at a glance. Starting with a temperature of about 81° at the equator, there is a gradual decrease to a temperature of about 29°, or 3° below the freezing point of fresh water,

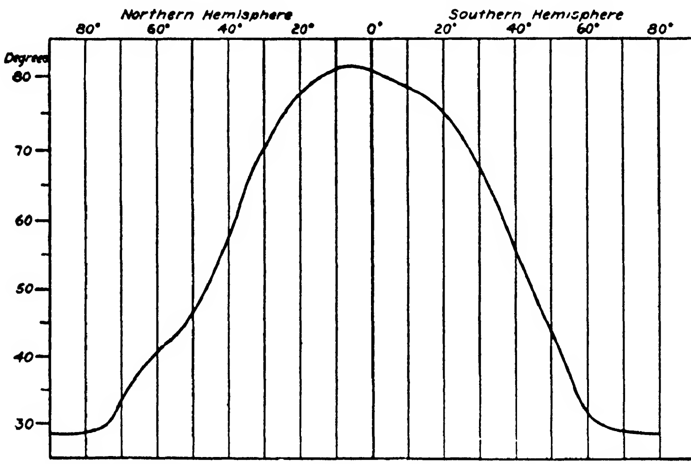

FIG. 14.—VARIATION OF TEMPERATURE OF SURFACE WATERS WITH LATITUDE (AFTER KRÜMMEL)

in the Arctic and Antarctic regions. The decrease in temperature with increasing latitude is not uniform, but as a rough rule the average temperature conditions of the surface waters of the sea may be summarized by the statement that, starting with the temperature of freezing water at the poles, there is an increase of half a degree in temperature for each degree decrease in latitude.

Although, as a general rule, the temperature of the sea varies inversely as the latitude, it is of interest to note

that the curve of temperature variation shows the highest temperature to come, not at the equator but in the northern hemisphere several hundred miles from the equator. In this respect, the sea reflects the variation of air temperature with latitude; for the highest average temperature of the air is not found at the equator but in about latitude 10° north.

Another feature brought out by the temperature curve is that the surface waters of the sea have a higher temperature in the northern hemisphere than in the southern. And this notwithstanding the fact that in the northern hemisphere the sea extends to the pole, while in the southern hemisphere the Antarctic continent limits the sea to about latitude 80°. Taking into consideration the areas involved, it has been computed that the average temperature of the surface waters in the northern hemisphere is 67°, while for the southern hemisphere it is 61°. For the sea as a whole, the average temperature of the surface waters comes out as 63°.

The temperature conditions pictured in Figure 14 are average conditions for the surface waters of the sea as a whole. If now we investigate conditions in the individual oceans we find the surface waters of the Pacific Ocean to possess the highest average temperature, namely 66½°. The Indian Ocean follows next with a temperature of 62¾° while the Atlantic is last with the only slightly lower temperature of 62½°.

As between the Atlantic and Pacific oceans there is the relatively large difference of 4° in the average temperatures of the surface waters. The reason for this difference is found primarily in the different configurations of the two oceans. The Pacific is roughly oval in shape, the greater part of its area lying in low latitudes. The Atlantic, on the other hand, is S-shaped and narrow in the low latitudes, the westward thrust of Africa and the eastward

thrust of South America diminishing very considerably its area in these low latitudes.

When the oceanographer comes to consider in detail the temperature conditions of the surface waters in the various oceans and seas, he finds that the broad features sketched in the preceding paragraphs must be modified in certain regions because of the intrusion of other factors. Such detailed consideration cannot be undertaken within the limits of the present publication; but to exemplify the actual distribution of temperature of the surface waters in a given basin, a brief discussion of the Atlantic Ocean will be of advantage.

In its southern half, the Atlantic presents a fairly regular variation with latitude of the temperature of its surface waters, as a glance at Figure 15 shows. From a temperature of about 29° along the icebound coast of Antarctica, the temperature increases regularly to about 79° at the equator. Throughout this entire area the lines of equal temperature, in the main, run approximately east and west. In the north Atlantic, too, from the equator to latitude 35°, variation in temperature with latitude is fairly regular. But northward of latitude 35° the lines of equal temperature are crowded together along the western shore and spread widely apart on the eastern shore so that these lines no longer run east and west.

This divergence from regularity on the part of the surface waters of the Atlantic north of latitude 35° is brought about by currents. Along the American coast the southerly flowing Labrador Current brings its cold waters from the Arctic regions, pouring them over the Great Bank of Newfoundland, so that off this coast as far south as latitude 45° N. the average temperature of the surface waters is but little above freezing. On the European shore, however, the Gulf Stream brings its freight of warm waters from the tropics so that it is not till latitude 70° N. is reached that

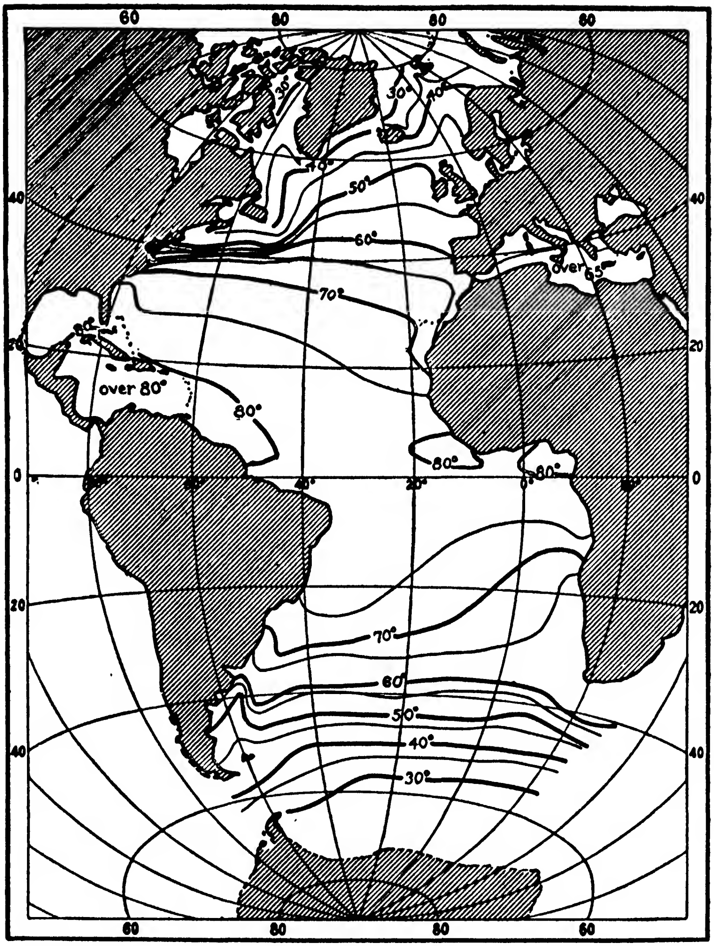

Fig. 15.—Temperature of Surface Waters of Atlantic Ocean (Adapted from Schott)

the waters here have the low temperature that is found fifteen hundred miles farther south on the western shore of the Atlantic.

The average temperature of the waters in the Arctic and Antarctic regions is about 29°, or 3° below the freezing point of pure water. Were it not for the salts carried in solution by the sea water, it could not maintain its liquid state at such a low temperature. Salts dissolved in water lower its freezing point, the greater the amount of dissolved salts, the lower the freezing point. On the customary salinity scale each unit increase in salinity lowers the freezing point of water one-tenth of a degree. Since sea water has a salinity of about 35, it can persist in liquid form at a temperature three and one-half degrees below the freezing point of pure water.

In color, too, sea water differs from pure water, which has a faint blue color. Sea water varies considerably in color. Near the coast, where fine mud particles are frequently held in suspension, the water may be somewhat turbid. Out in the open sea the color ranges from green to blue, depending on the microscopic plant and animal life inhabiting the water. The color appears to vary also with the weather; under a cloudless sky the water is bluer, while an overcast sky gives the water a more greenish appearance. At sunrise and at sunset still other color effects may be seen. In general, within tropic and subtropic regions the open sea is blue, while green is the prevailing color of the waters in colder regions.

CHAPTER XII

THE WATERS OF THE DEPTHS

THE determination of the characteristics of the subsurface waters of the sea presents a more difficult problem than that relating to the surface waters. To begin with, the problem is complicated by the addition of another dimension, for the characteristics of the water at different depths all the way to the bottom must now be studied. Furthermore, the simple method of securing a sample of the water to be studied, which is used in the case of the surface waters, is no longer applicable. Special contrivances must be devised for obtaining samples of the water from the depths.

The instruments designed for the purpose of securing samples of the subsurface waters are known by the general name of water bottles. Various forms have been used, but in general a water bottle consists of a metal tube open at both ends which can be closed at any desired depth. It is let down on a wire into the sea with both ends open so that it slips through the water; and at any depth, therefore, it contains the water of that depth. When it reaches the depth from which a sample is desired the ends are closed either by letting down a weight on the wire which strikes the closing mechanism, or in some forms the closing is done automatically as soon as the water bottle is pulled upward. By this means, water from any desired depth may be obtained.

As soon as a sample of water from the depths is secured, its salinity can be determined by any one of the methods described for the surface waters. It is evident, however,

that in the open sea such observations are time-consuming and therefore costly. And while a number of observations on the salinity of the subsurface waters have been made, they are sufficient to give but a very general view of the distribution of the salinity in the depths of the sea.

The surface waters, it will be recalled, exhibit relatively large differences in salinity, the variation with latitude, as represented in Figure 13, being especially prominent. But, as we go down into the depths of the sea, differences in salinity as between different regions become less and less pronounced, so that at a depth of about a mile there is generally but little difference in the salinity of the water. The Atlantic Ocean, in which conditions are best known, may be used as an illustration.

Starting at its southern boundary, the surface waters of the Atlantic have a salinity of about 33. Going northwards this increases with more or less regularity until a salinity of a little more than 37 is reached in latitude 20° S., after which there is a decrease to a value of about 34½ about 300 miles north of the equator. From this point there is again an increase to a salinity of 37½ in latitude 25° N., this being followed by a decrease to a salinity of about 30 or even less in the Arctic waters.

At a depth of 200 fathoms or 1,200 feet the differences in salinity of the waters of the Atlantic are less pronounced. Starting again at the southern boundary we find the water with a salinity of 34½, and in going northward as far as the equator there is but little increase, the water at the equator having a salinity of but 35. Northward of the equator there is another slight increase to a little over 36 in latitude 30° N., after which comes a decrease to a salinity of a little less than 35 in the Arctic waters.

At a depth of 600 fathoms, or a little over half a mile, there is still less difference in the salinity of the Atlantic Ocean waters. At its southern end the salinity is about

34¾, rising gradually to a maximum of 35¼ in latitude 30° N. and then declining again to about 34¾ in the Arctic regions. At this depth, therefore, throughout its length of more than than ten thousand miles from the Antarctic to the Arctic, the waters of the Atlantic Ocean differ less than a single unit in salinity.

Now, obviously, in our cursory survey of the salinity of the waters of the Atlantic at different depths, only the larger features could be noted. In certain regions near the coast, local conditions may give rise to areas with a salinity different from that which prevails over the greater part of that stretch of ocean. For example, off the entrance to the Mediterranean Sea there is an area of high salinity even at a depth of 600 fathoms. This, however, does not invalidate the general rule of an increasing uniformity in the salinity of the waters of the deeper parts of the sea.

The data given above with respect to the salinity at the three depths show that, with the exception of the relatively small regions in the high latitudes, the waters of the Atlantic Ocean become gradually less saline from the surface to the 600-fathom depth. Thus, taking the stretch of ocean lying 20° either side of the equator, we find an average salinity of very nearly 36 at the surface, a little more than 34¾ at the 200-fathom depth and a little less than the latter value at the 600-fathom depth.

The salinity in the depths of the oceans is not sufficiently well known to justify definite statements regarding its variation with depth. There is evidence, however, that, in general, the salinity diminishes somewhat from the surface to a depth of about a mile, beyond which there is a slight increase to the bottom. In regard to salinity, therefore, the difference between the surface water and that of the depths is but slight. It has been estimated that the surface waters of the sea have a salinity of about 34½ while the waters of the sea as a whole have a salinity of about 34¾.

With a value for the salinity of the sea as a whole, we are in a position to determine the total amount of salts contained in the sea. A cubic foot of sea water weighs approximately 64 pounds, which means that a cubic mile of sea water weighs 4,710,334,464 tons. The average salinity of 34¾ means that every thousand tons of sea water contains 34¾ tons of salts in solution. With a volume of 329 million cubic miles for the sea, simple multiplication gives the total amount of salts in the sea, in round numbers, as 54 quadrillion (54,000,000,000,000,000) tons.

In our consideration of the composition of the salts contained in sea water, on page 130, the proportions of the five principal salts were given. These five salts constitute 99½ per cent of the total salts in solution; and with the percentages given it is a simple matter to calculate the total amount of each of these salts contained in the sea. The results of such calculations are impressive in the amounts of their totals and bring out vividly the wealth of the sea in these substances which are of importance in industry. Such calculations, however, need not detain us here. Rather, let us consider the remaining one-half of one per cent of the salts which was stated to consist of calcium carbonate, magnesium bromide, and traces of other substances.

Water is an almost universal solvent. Hence, besides the seven salts already enumerated, the sea contains, also, traces of numerous other substances. Indeed, of the eighty-odd elements known to the chemist about thirty have been found in sea water, although many of these in such extremely small doses that special methods must be used to detect their presence. Thus, gold and silver have been shown to exist in sea water, but in such minute quantities that a million tons of sea water contains perhaps one-tenth of a pound of each of these metals. Extremely small as this value is per unit volume of water, calculation proves the total amounts of these metals in the sea to be of sur-

prising magnitude. Thus, taking the proportion of one-tenth of a pound of gold to a million tons of water, we find that the sea contains something like seventy-five million tons of gold. And while such calculations can lay no claim to precision, they nevertheless do indicate that as a potential mine of the precious metals the sea must be ranked high.

For the surface waters of the open sea we have found that there are no daily and seasonal variations in salinity such as characterize the temperature of the water. Within the depths conditions are even less variable than at the surface; so that, so far as periods measured in months or years are concerned, the salinity of the waters of the sea as a whole may be regarded as constant. But with regard to periods reckoned in centuries, does the salinity of the sea remain constant?

This question really involves two separate questions, one relating to the constancy of the dissolved matter in the sea, and the other relating to the constancy of the volume of the ocean waters. With regard to the first, we know that the drainage waters from the land which find their way into the sea carry with them matter in solution. In the aggregate this dissolved matter brought into the sea, annually, must total to a very considerable amount. In 1887 the English oceanographer, Sir John Murray, estimated the amount of saline matter annually carried into the sea by rivers to be nearly five billion tons. About a quarter of a century later the American geophysicist, F. W. Clarke, made another calculation using more recent and more extensive data and arrived at a figure of about 2.7 billion tons. While these figures must be regarded somewhat in the nature of estimates, they nevertheless bring out clearly the very large amount of dissolved matter carried annually into the sea from the land.

At first glance, therefore, it would appear unquestion-

able that the amount of matter carried in solution in the ocean waters is increasing continually. But the problem is not quite so simple. For on analysis it is found that river water has a decidedly different composition from sea water. Thus, while sodium chloride makes up more than 75 per cent of the salts in sea water, it constitutes but a little over 2 per cent of the salts in river water. Furthermore, of the salts in sea water nearly 90 per cent are chlorides and less than half of one per cent carbonates. In river water, on the contrary, carbonates make up nearly 60 per cent of the salts and chlorides but little over 2 per cent. Sea water is, therefore, not merely concentrated river water. Chemical reactions and changes of one kind or another take place in the sea which transform the material carried into it from the land.

Some of the salts carried into the sea are withdrawn by the plant and animal life in the ocean. Thus, carbonate of lime is withdrawn by organisms to form shell and coral, and, in a similar manner, silica is withdrawn by such organisms as sponges and diatoms. Potassium and iodine are withdrawn by certain kinds of seaweeds, while other salts are withdrawn, too, in connection with chemical changes, the final products of which are found on the bottom of the sea. However, taking everything into consideration, it appears that the material dissolved in the sea is probably increasing continually at a very slow rate.

If, therefore, the volume of the ocean waters remains constant we cannot escape the conclusion that the salinity of the sea has been increasing from the very beginning. But does the quantity of sea water remain constant? In our consideration of the level of the sea in Chapter X, this latter question was touched on briefly and several causes mentioned which are adequate in bringing about a change in the volume of the ocean waters. The geologist studying the records of the rocks has become convinced that during

its long history the earth has passed through wide climatic variations. Three and perhaps four times, great ice sheets have covered large parts of its surface, while in between these glacial periods more genial conditions obtained. During the glacial epochs a considerable volume of water was abstracted from the sea to be spread over the land in the form of ice; and during the warmest periods of the genial epochs the volume of the sea would contain the maximum amount of water. It has been estimated that if the ice that now covers the Antarctic continent were to melt, it would raise the level of the sea by about one hundred feet.

The question of whether or not the salinity of the sea is increasing thus involves factors with respect to which there are no precise data. Despite the considerable influx of matter from the land, the volume of the ocean waters is so great that any change in the salinity must be so small as to escape detection except over periods measured in hundreds of centuries.

One further phase of this question of the salinity of the sea is of interest, in that it has been used in estimating the age of the ocean. Of the substances brought into the sea from the land, most do not tend to accumulate in the water since they interact with each other to form the sediments on the bottom of the sea or are withdrawn by plant and animal life. Sodium, however, appears to be subject to no such changes, and we are forced to conclude that in regard to this element there has been a steady accumulation from the time when the sea first came into being. If we assume a uniform increase in the sodium content of the sea, then obviously the age of the sea is given by dividing the total amount of sodium now in the sea by its annual increase.

The total quantity of sodium in the sea is readily derived, at least with a fair degree of approximation, from the fact that sodium constitutes 30½ per cent of the total matter in solution. The annual contribution of sodium

through drainage waters can likewise be calculated with some degree of approximation. But this latter figure must certainly have varied throughout geologic time. Making such allowances for this variability as seem most reasonable, the geologist arrives at the conclusion that the age of the sea is something like one hundred and eighty million years.

Just as in regard to salinity the waters of the depths are less variable than those of the surface, so also in regard to temperature the depths of the sea are more uniform than the surface. At a depth of about five fathoms the daily variation in temperature disappears. And even the annual variation, which over the greater part of the surface of the sea amounts to about ten degrees, decreases rapidly as we go down into the depths, and when one hundred fathoms is passed disappears altogether. Below this depth the temperature remains constant from winter to summer.

How is the temperature of the water in the depths of the sea determined? Several methods are used. By insulating the water bottles employed in securing samples of water from the depths for the determination of salinity, no change takes place in the temperature of the sample of water and its temperature may then be determined as soon as it is hauled aboard the ship. This method possesses the advantage of securing a sample of water from any desired depth for the determination of both the salinity and temperature. Several forms of such water bottles are in use. The type known as the Pettersson-Nansen water bottle, which was devised by the Scandinavian oceanographers Otto Pettersson and Fridtjof Nansen has been used considerably. It consists essentially of a central chamber surrounded by two concentric shells of insulating material. When the water bottle is closed at the desired depth the water in the central chamber is insulated by two layers of water between the insulating shells and does not change in temperature even when being hauled up from a depth of

five hundred fathoms. A thermometer is so fixed in the apparatus that its bulb is immersed in the water of the central chamber, so that its temperature can be read as soon as the water bottle is hauled aboard.

For very great depths there are certain corrections necessary to the temperature as determined by water bottles because of the very great difference in pressure as between the depths and the surface. For great depths, therefore, a reversing thermometer is used. This is a mercury thermometer constructed with an S-shaped bend in the capillary tube near the bulb, and within this bend the tube is constricted. The thermometer is let down on a wire to the desired depth in an upright position and then as it is hauled up it is reversed, either by means of a weight or automatically. On reversing, the mercury column breaks at the constriction, that part of the mercury column above the constriction sinking down to the end of the tube. On being hauled aboard, the length of this severed column gives the temperature at the desired depth.

Within the deeper parts of the sea the pressure is very great and the deep-sea thermometer must be specially constructed to withstand this great pressure. Ordinary thermometers, when lowered to depths of more than one thousand fathoms, are crushed. The reversing thermometer is enclosed in a thick strong-walled glass tube from which the air is exhausted and the ends then hermetically sealed. The lower part of the enclosing tube is shut off from the upper part and partly filled with mercury to secure a rapid conduction of heat to the thermometer bulb within. Reversing thermometers are now so accurately made that they give the temperatures of the depths with a precision better than half a tenth of a degree.

Since the temperature of the sea is due primarily to the direct heating by the sun, it is to be expected that the surface water will be warmer than the water of the depths.

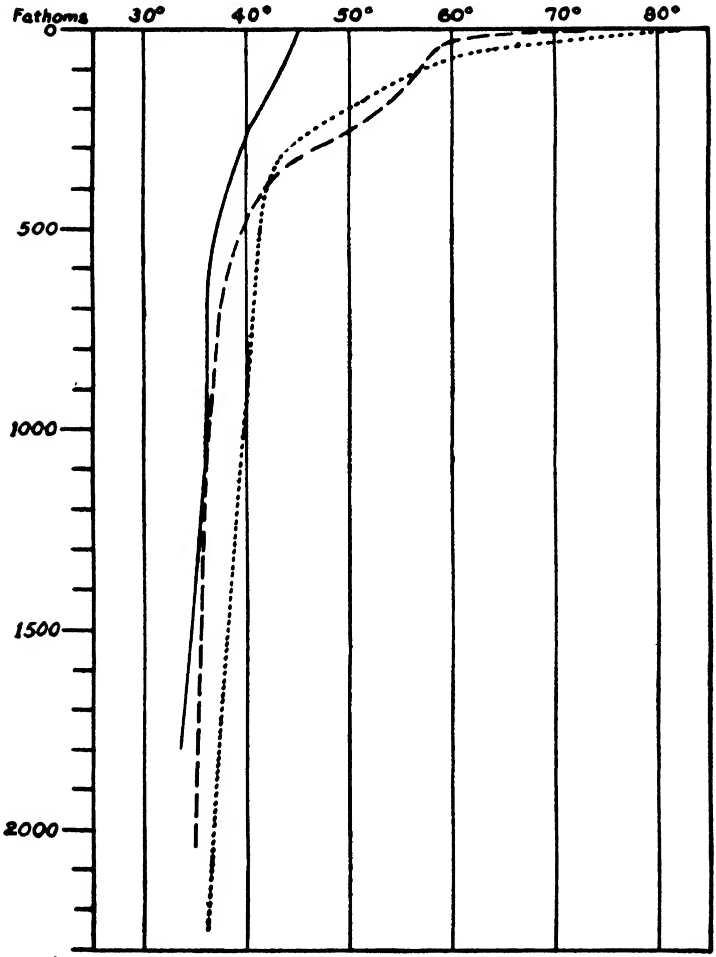

Fig. 16.—Observed Temperature at Various Depths at Three Stations

And that, generally, is the temperature condition of the sea. Except in the icy regions of the high latitudes, and in certain areas where peculiar conditions obtain, the temperature of the oceans decreases from the surface to the bottom. This decrease, however, is not uniform, the most rapid fall in temperature taking place in the upper layers of the water. The variation of temperature with depth at three different stations is illustrated in Figure 16.

The dotted line represents the temperature conditions at a station in the central part of the Atlantic Ocean near the equator. The dashed line represents the conditions in the northern part of the Pacific Ocean and the full line, conditions in the southern part of the Indian Ocean. These temperatures were observed by the *Challenger* expedition during its famous cruise between the years 1872 and 1876. The surface temperatures were quite different at the three stations, the difference as between the stations in the Atlantic and Indian oceans amounting to nearly forty degrees. These differences, however, rapidly disappear with increasing depth, at 400 fathoms being but five degrees and at the bottom but three degrees.

The three curves of Figure 16 bring out several important facts. In the first place, the decrease in temperature is most rapid in the upper layers of the water, after which it is very gradual. Secondly, the curves bring out the fact that below the 400-fathom depth the water of the sea is cold, having a temperature of about forty degrees. Thirdly, it is clear that the water near the bottom is but little above the freezing point of pure water. Furthermore, the variation of the temperature with latitude, which is the dominant feature at the surface, becomes less pronounced below the surface and completely disappears in the deeper parts of the sea.

At different places the detailed features of the temperature conditions may be somewhat different than portrayed

in Figure 16; but by and large they represent the temperature conditions of the open sea. As a rule, the highest

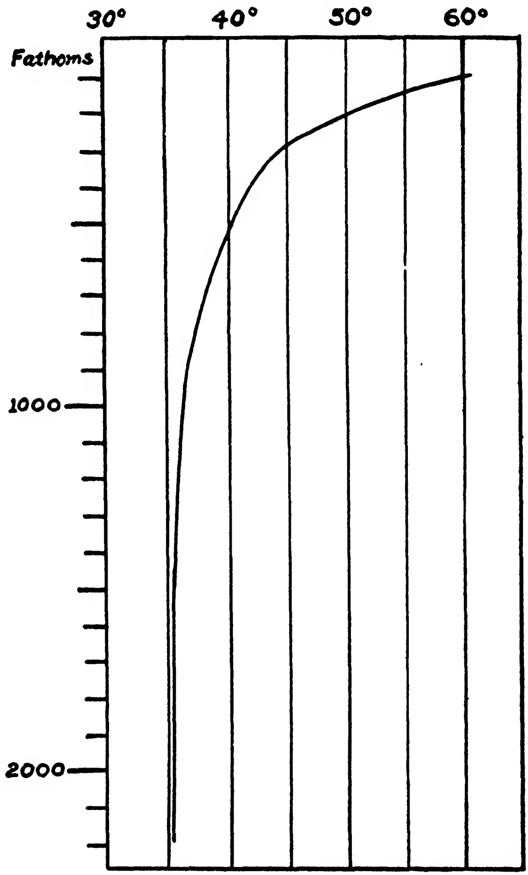

FIG. 17.—GENERALIZED CURVE OF VARIATION OF TEMPERATURE OF SEA WATER WITH DEPTH

temperature is found at the surface, while the temperature of the great mass of the water below the surface is but little above the freezing point of water. From the observa-

tions made by the *Challenger* expedition—which covered about three hundred and fifty stations in the three oceans—Sir John Murray averaged the temperatures for the different depths from one hundred fathoms to twenty-two hundred fathoms, the results being shown graphically in Figure 17.

Figure 17 emphasizes the facts adduced from the three stations represented in Figure 16. The rapid fall in temperature to the depth of 400 fathoms, the very gradual fall thereafter, and the low temperature prevailing within the depths below 400 fathoms—these are clearly brought out by the curve. As a whole, therefore, the sea comprises a vast reservoir of cold water.

The curve of Figure 17 represents conditions as averaged for the sea as a whole. When the temperature conditions are studied in detail the effects of local conditions become prominent. For example, in the broad belt lying thirty degrees each side of the equator the easterly trade winds drive the warmer upper layers of the water towards the western portions of the oceans. As a result the temperature at the 100-fathom depth is considerably higher toward the western rims of the oceanic basins than in the eastern parts. But the discussion of the details of the temperature distribution within the sea obviously would lead us too far afield.

Two features of the temperature of the water within the depths are so striking as to demand further consideration. The first relates to the fact that throughout the whole extent of the sea, from the tropics to the polar regions, there is but little difference in the temperature of the water within the deeper parts of the sea. This is in marked contrast to the conditions obtaining in the surface waters of the sea in which, it will be recalled, there is a difference of as much as fifty degrees between the tropics and the polar regions.

The second feature relates to the fact that within the

deeper parts of the sea the temperature of the water is extremely low, only little above freezing. That this should be the case in the polar regions is not surprising, for there the surface waters likewise are close to freezing. But in the tropics the sea is very warm on the surface, having a temperature of as much as eighty degrees. How comes it then that here, too, the bottom layers of the water are so cold?

The low temperature of the water in the deeper parts of the sea finds ready explanation in a slow bottom current from the polar regions toward the equator. Later, in studying ocean currents, we shall see that forces are at work that give rise to this movement within the depths toward the equator. This bottom polar current toward the equator explains, too, why there is practically no difference in the bottom temperature of the sea from the tropics to the polar regions. In this connection, however, it may be of interest to note that a well-known oceanographer regarded the cold waters of the depths as a heritage from the time of the last ice age. According to this view it is only the upper layers of sea water that have become warmer with the gradual change to more genial conditions since the last ice age, so that the water in the deeper parts of the sea constitutes, as it were, fossil water.

The temperature distribution within the depths represented by Figure 17 holds for the sea outside the icy regions of the high latitudes. In these latter regions the temperature conditions are different. As we found in our consideration of the surface temperatures in the preceding chapter, the surface water in these regions has a temperature close to the freezing point; as a result, there is very little difference in the temperature of the water from the surface to the bottom. Furthermore, instead of the water here decreasing in temperature with increasing depth, the temperature within the depths is frequently found to be some-

what higher than at the surface, since the latter water is in direct contact with the ice.

Within the tropics the fall in the temperature of the sea is so rapid that as between the surface and a depth of four hundred or five hundred fathoms there is a difference of as much as forty degrees. This condition holds out interesting possibilities of usefulness. For, theoretically, the difference in the vapor pressures of the warm surface waters and the cold waters of the depths may be used as the motive power of a heat engine. Recently, two French engineers, Georges Claude and Paul Boucherot, have put forward plans for the utilization of this thermic energy of the sea. A further possibility of usefulness lies in the amelioration of the enervating effects of tropical climates by the direct cooling of living quarters by means of the water of the depths.

For the purpose of study it is convenient to consider the surface waters separately from the waters of the depths. But it must be kept in mind that from the surface to the bottom the water of the sea constitutes an organic entity, each part affecting every other. The temperature of the surface waters we have found to vary strikingly with latitude, from eighty degrees at the equator to less than thirty degrees in the polar regions, as represented in Figure 14. Within the depths, however, the temperatures are more nearly uniform. Taking the waters of the sea as a whole, how much variation in temperature is there in the different zones? This question is answered graphically by Figure 18.

As compared with the temperature conditions at the surface, the temperature of the sea as a whole is shown by Figure 18 to vary but little with latitude. Indeed, to bring this variation out clearly it was necessary to make the temperature scale in Figure 18 twice that of Figure 14. From the polar regions to the equator the difference in the temperature of the whole mass of sea water is but ten degrees.

And as a whole the sea is cold, its average temperature even in the tropics being but forty degrees.

Of the individual oceans, the Atlantic with an average temperature of 39.2 degrees is the warmest; the Indian Ocean is next with a temperature of 38.9 degrees while the Pacific with an average temperature of 38.7 degrees is the coldest. As regards the temperature of the whole mass of water of each of the oceans, the conditions at the surface are reversed. For it will be recalled that the surface water of the Pacific Ocean was warmest while that of the Atlantic was the coldest. A number of factors conspire to bring about this reversal of conditions, but it is of interest to

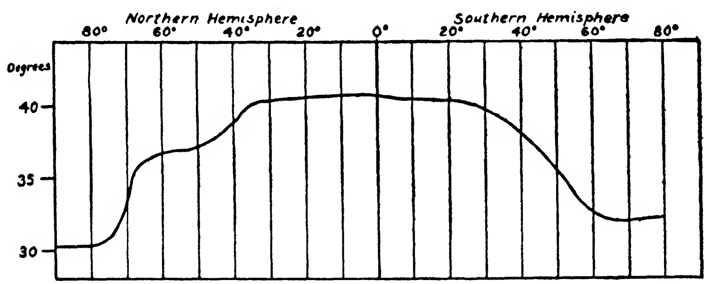

FIG. 18.—TEMPERATURE VARIATION OF THE SEA WITH LATITUDE

note that as regards the temperature of the individual oceans they range themselves inversely as their average depths. The deepest ocean—the Pacific—is the coldest, while the shallowest—the Atlantic—is the warmest. This is in accordance with the vertical temperature distribution of the sea.

Within the dependent seas the temperature, as a general rule, decreases with increasing depth. Being more circumscribed in extent, the effect of latitude becomes very marked also in comparing the temperatures of the different dependent seas with one another. Thus, the Persian Gulf stands highest in the list of dependent seas ranged in accordance

with temperature, its waters averaging seventy-five degrees, while the Arctic Sea is at the foot of the list with a temperature of thirty-one degrees.

In discussing the methods used in measuring the temperature within the depths of the sea, mention was made that the thermometer must be specially constructed to withstand the great pressures within the depths. At any given depth there is a definite pressure due to weight of the mass of water above that depth. Since a cubic foot of sea water weighs approximately 64 pounds, it follows that the pressure of a column of water, one foot high, is 0.44 pound per square inch. At a depth of a mile, therefore, the pressure is more than one ton per square inch, while at a depth of three miles it is over three and a half tons. Under such great pressures any thin-walled instrument containing air hermetically sealed will collapse. A piece of wood or cork, which on the surface of the water floats because of the large number of air cells it contains, will sink in the depths of the sea because of the collapse of these thin-walled air cells; and for this reason wood or cork is not suitable as a float in great depths.

The enormous pressure to which the waters within the depths of the sea are subject has given rise to the belief that in the depths the water becomes so dense that bodies sinking below the surface do not reach the bottom, but float at some level where the density of the water is the same as that of the body. Sir John Murray tells that after a funeral at sea during the *Challenger* expedition, a deputation of seamen came to inquire whether their departed comrade's body, which was committed to the deep with a heavy weight attached, would go right down to the bottom or would it "find its level" and there float with the current.

In this connection, however, it is to be noted that water is but very slightly compressible. Hence, even under the enormous pressures found within the depths of the sea

its density is changed but very little. It follows therefore that any body that sinks to the bottom in shallow water will sink to the bottom just as readily in the deepest part of the sea.

CHAPTER XIII

ICE IN THE SEA

THE regions lying in the higher latitudes are characterized by extremely low temperatures for many months of the year. As a consequence, ice forms a prominent feature of the sea in the higher latitudes of both the northern and southern hemispheres. In the search for the Northeast and Northwest passages, and in the long struggle for the attainment of the poles, the ice of the sea constituted both a formidable obstacle and a dangerous hazard.

But even in the lower latitudes of the temperate regions ice may be found in the sea, being carried thither from the higher latitudes by ocean currents. The serious menace to navigation which such ice constitutes was brought forcibly to the world's attention in 1912. Early in April of that year the great steamship *Titanic*—which at that time represented the highest achievement in shipbuilding—started on her maiden voyage from England to the United States. On the regular sailing route, and when more than halfway across, she struck an iceberg and sank with a loss of more than fifteen hundred souls.

The ice that occurs in the sea comes from two different sources. In part it originates in the sea itself by the freezing of sea water; and in part, too, it comes from the land, being brought down to the sea by rivers and glaciers. It is from the latter source that the great icebergs come.

The salts dissolved in sea water lower its freezing point below that of pure water. On the customary salinity scale, in which a unit represents one part of salt in a thousand

parts of water, each unit increase in salinity lowers the freezing point of water approximately by one-tenth of a degree Fahrenheit. Sea water, on the average, has a salinity of about 35; hence its freezing point is about three and one-half degrees below the freezing point of pure water, or about twenty-eight and one-half degrees.

The freezing of sea water is an extremely complex process. When freezing begins, only pure ice is formed, the salts not entering into the ice until a temperature of about 17½° is attained. As the temperature becomes lower than this more and more of the salts in the sea water enter into the ice being formed. As a consequence of this, sea ice is less saline than the sea water out of which it was formed; furthermore, the salinity of sea ice formed from sea water of a given salinity varies in accordance with the temperature at which it was formed.

The salinity of sea ice varies also in accordance with the rapidity with which the freezing takes place. If the freezing proceeds slowly, the concentrated brine, left when the pure ice crystals have formed, has time to separate out from between the crystals. But when the freezing takes place rapidly, some of the brine is trapped between the ice crystals before it can separate out and is thus retained by the ice. Slowly formed sea ice is therefore less saline than rapidly formed ice.

Even after sea ice with a definite salinity has formed, this salinity is subject to change. For, as a general rule, the older the ice, the less saline it becomes. This is due to the fact that the brine between the ice crystals tends to work its way downward out of the ice. This generally takes place during the periods of relatively mild temperature. So that sea ice more than a year old is frequently quite pure, a fact which polar explorers take advantage of in securing ice for melting for drinking water.

On freezing, ice expands so that it is lighter than an equal volume of water; and, as a consequence, it floats on the water. The density of sea ice varies somewhat, but on the average it is about nine-tenths that of sea water. This means that when floating free in the water the ice will have nine-tenths of its mass submerged. This, however, is not synonymous with the statement that the height above water is one-ninth that below water, for the relative heights of the emerged and submerged portions depend on the cross-sectional areas of the two parts. If a mass of ice tapers much from bottom to top, a much smaller part of it will be submerged than if its cross-sectional area were uniform from top to bottom.

Ice is a poor conductor of heat, its conductivity being less than one-hundredth that of iron. Coupled with its low density, the poor conductivity is of great importance in restricting the volume of ice formed during the winter. For the floating mass of this poor heat-conducting material effectually shields the water below it from the freezing temperatures that prevail in the air. Even in the excessively long and cold winters of the Arctic and Antarctic regions the layer of ice that is formed by the freezing of sea water during a single winter is less than ten feet, and as a rule not more than five or six feet.

In the polar regions masses of sea ice twenty or more feet in thickness are frequently encountered, but these arise not from the freezing of a layer of water of that thickness but from other causes. Snowdrifts will at various times accumulate on the sea ice and then be frozen on to the ice, thus creating masses of considerable thickness. During storms also, large masses of ice may be piled atop one another and frozen together. It is in such wise that the hummocky ice packs of the polar regions arise.

Sea ice is one of the most characteristic features of the Arctic waters. Forming on the surface of the water as

soon as the temperature of the air goes below freezing in the fall, the ice increases gradually in thickness until the middle of winter when it is from five to nine feet thick. After this there is but little increase, evaporation above and melting below just about counterbalancing the addition due to freezing. The ice, however, does not form in a sheet of uniform thickness. As the ice cover is forming, tide and wave break it apart into individual floes and under the influence of the wind these floes are pushed against and over one another and frozen together to form larger masses. As the winter progresses, large fields of ice result which finally become consolidated into the hummocky, impenetrable ice pack. In this process great pressures are developed and masses of ice up to fifteen feet or more in height are pushed up vertically.

Apart from the local movements which wind and wave and tide impose on the ice, it is subject also to a slow but widespread drift even in winter when the ice pack has attained its greatest extent. It was this drift that Nansen made use of in his daring expedition in the *Fram*, when he worked her into the ice pack and allowed her to be frozen in near the New Siberian Islands in September of 1893. Carried by the ice in a westerly direction for nearly three years the *Fram* came free of the ice north of Spitzbergen in June of 1896, after having drifted nearly a thousand miles. During this time she was subjected to enormous pressures and it was only her great strength and special build which saved her from the crushing effect of these pressures. The sides of the *Fram* were so designed that when caught between ice masses the pressure would tend to lift her.

By the end of the long polar night the ice pack has reached its greatest development. With the beginning of the polar day the sun begins the work of disintegration. In June and July the ice pack becomes broken up into individual floes which gradually succumb to the combined

attacks of melting water and warmer air. Large areas now become free of ice. The extent of these ice-free areas varies from year to year, depending on climatic conditions. But in no summer are the Arctic waters wholly free of ice—in fact, not even half free. The disintegration is further aided by currents which carry the ice floes southward where they are melted in the warmer waters of the lower latitudes.

In the Antarctic, sea ice is not so prominent a feature as in the Arctic. This difference in the two polar regions is a result of the difference in distribution of land and sea in the two regions. In the Arctic we have an ocean surrounded by continental land masses. During the long polar winter, therefore, the surface of this ocean becomes overlaid with a covering of sea ice. In the Antarctic we have the polar region occupied by a continent covered with an ice cap. This ice cap extends out to sea, forming in many places a barrier a hundred or more feet in height. But this ice is primarily land ice and not sea ice. The ice pack that forms in the Antarctic is therefore only in part made up of sea ice, the larger part being made up of fragments broken off from the land ice.

It is this difference in the origin of the ice in the waters of the polar regions that makes sea ice the characteristic feature of the Arctic seas, and icebergs the characteristic feature of the Antarctic waters. The south polar ice cap extends in all directions, making possible a large number of icebergs in the Antarctic. On one Antarctic expedition it was estimated that nine hundred icebergs could be seen at one time.

An iceberg is a large fragment broken off from a glacier. On reaching the sea the front of the glacier continues the advance along the sea bottom until it reaches a depth sufficient to float it. The upward pressure on the floating end gives rise to stresses within the mass of the glacier. Additional stresses arise in consequence of the floating portion

rising and falling with the tide. Cracks and fissures result and finally a mass of ice is broken off—an iceberg is born. Technically this is known as "calving." Some glaciers are reported to calve at the rate of one iceberg a day on the average.

Icebergs vary greatly in size and shape. The largest icebergs occur in the Antarctic, fed from the glaciers of the immense south polar ice cap. The surfaces of these glaciers along the ice barrier are frequently flat; hence the tabular iceberg is a characteristic form in the Antarctic. Such icebergs are frequently of immense size, several miles long and towering more than a hundred feet above the surface of the sea. There are reports of Antarctic icebergs more than fifty miles long and several hundred feet high. The greater number, however, are not more than a quarter of a mile in length and a hundred feet in height.

The greater part of an iceberg lies below the surface of the sea. If it were of uniform cross section and of compact ice the total height of an iceberg would be ten times the height of the portion above sea level, since the density of ice is nine-tenths that of sea water. But an iceberg is neither of uniform cross section nor is it made up wholly of compact ice. Cavities of one sort or another abound and almost without exception the cross-sectional area of the submerged part is larger than the emerged part. Hence the depth to which the submerged portion reaches is never as much as nine times the height of the emerged part. From such measurements as have been made it appears that generally the total height of an iceberg is six or seven times the height of the emerged part.

The Antarctic icebergs, as a rule, have a longer life than the Arctic icebergs. The latter seldom endure for more than two years; the former, however, may reach an age of as much as ten years. This difference is due not only to the greater mass of the Antarctic icebergs, but also to the fact

that for the same latitude the sea in the southern hemisphere has the lower temperature, so that melting does not proceed at as rapid a rate. Carried northward by currents, the Antarctic glaciers may at times drift below latitude 40° South; but that latitude may be taken as the northern limit of iceberg drift in the southern hemisphere.

In the northern hemisphere, too, the fortieth parallel of latitude may be taken as marking the lower limit of iceberg drift. This, however, applies only to the Atlantic Ocean, for the North Pacific Ocean is destitute of feeding grounds for icebergs. No extensive ice-covered land masses occur here to give rise to large glaciers and hence no icebergs occur in this ocean. But, notwithstanding the more limited distribution of icebergs in the northern hemisphere, it is here that they are of greater importance, for their drift lies athwart the most frequented steamer lanes between the old world and the new.

Most of the icebergs in the North Atlantic Ocean come from Greenland, and more particularly from the glaciers that empty into the fiords fronting Baffin Bay. After calving from these glaciers, they come within the sweep of the southerly current that flows along the western shore of Baffin Bay. This carries them out through Davis Strait into the Labrador Current, which finally brings them into the region of the Grand Banks. Schematically this is shown in Figure 19, in which the arrows represent the directions of flow of the currents.

While the icebergs are calved both in summer and in winter, they are free to move out into the open sea only in summer. For in winter there is a barrier of ice formed in the fiords which hems the icebergs in, keeping them within the fiords. With the coming of summer the barrier of fiord ice breaks up; the icebergs now have a free outlet and they begin their southerly journey.

From the coastal waters of Greenland to the Grand

Banks is a distance of approximately eighteen hundred miles. This distance the icebergs cover in about a year.

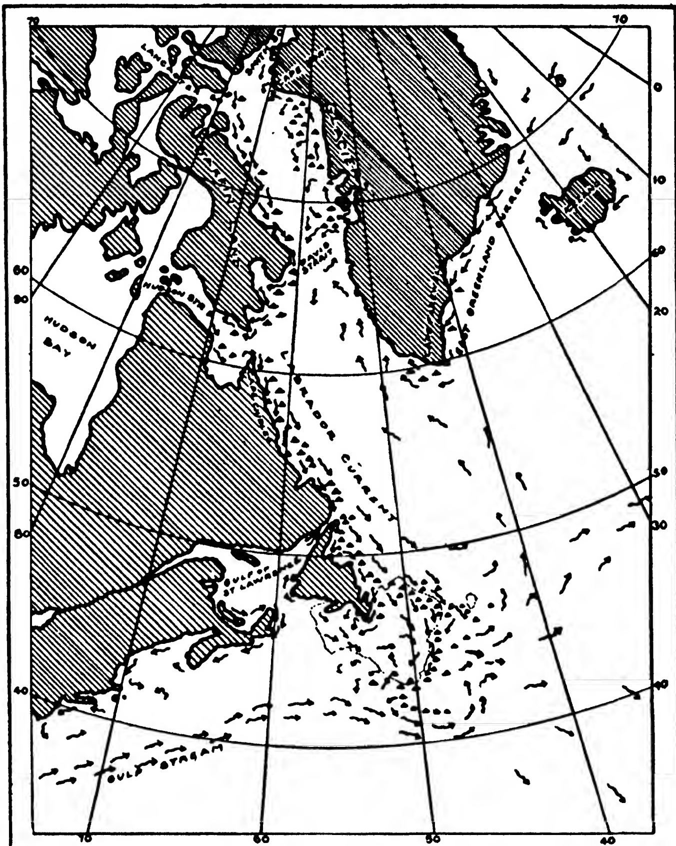

FIG. 19.—DRIFT OF ICEBERGS IN NORTH ATLANTIC OCEAN (ADAPTED FROM U. S. HYDROGRAPHIC OFFICE "PILOT CHART OF THE NORTH ATLANTIC OCEAN," MARCH, 1927)

During their southerly drift many of the icebergs become grounded along the Labrador coast, where they slowly dis-

integrate. A number of them, however, reach the region south of Newfoundland. And while bergs may be found in this region during all months of the year, they are most frequent during the months of April, May, and June, and least frequent during the months of November, December, and January.

From Figure 19 it is seen that the warm waters of the Gulf Stream flow past the Tail of the Grand Banks. It is here that the melting and disintegration of the icebergs proceeds most rapidly. The average iceberg reaching this region survives about two weeks. If it reaches a still lower latitude it comes within the influence of still warmer water in the Gulf Stream and here it can last but a week.

The number of icebergs that drift down south of Newfoundland, and thus become potential menaces to shipping, varies greatly from year to year. By actual count there were more than a thousand during the year 1912 and only eleven during the year 1924. On the average, about four hundred may be expected within a year, with May showing the greatest number, about one hundred and thirty. The iceberg season in this region extends, generally, from the beginning of March till the end of June, these four months accounting for more than three hundred of the average yearly crop of four hundred bergs. These months, therefore, constitute the season during which ice is a menace to transatlantic shipping.

It was in April of 1912 that the *Titanic* sank. The year following this disaster, an International Conference for the Safety of Life at Sea was held in London. As a result of the conference, fourteen maritime nations agreed to share the cost of an International Ice Patrol of that part of the North Atlantic which is endangered by ice during the ice season. The United States Government was entrusted with the management of the patrol, the duty being performed by the U. S. Coast Guard.

Every year the Coast Guard details two of its best-equipped ships for the patrol service. From March through June—and into July if necessary—those two vessels alternate in cruising within the ice regions for periods of fifteen days. The object of the patrol is to locate the icebergs menacing the North Atlantic steamship lanes. In doing this it is necessary to determine the southerly, easterly, and westerly limits of the ice and keep in touch with it as it moves southward. Twice daily, radio broadcasts are sent out giving the location of the bergs, thus forewarning the navigator.

In connection with the ice-patrol work, the patrol vessels are also engaged in carrying out a program of oceanographic investigations. This is being done primarily for the purpose of solving two practical problems, namely, the forecasting of the number of bergs that are likely to come down, and the forecasting of their movements on arrival at the critical area in the vicinity of the Tail of the Grand Banks. In the attempt at solving these practical problems, the patrol vessels are securing temperature, density, salinity, and other data which are throwing light on other oceanographic problems.

Against the background of the open sea the iceberg is so striking a sight that its size is usually overestimated. The North Atlantic icebergs are much smaller than those found in the Antarctic Ocean. Transatlantic vessels frequently report having seen, in the distance, icebergs half a mile long and three hundred to four hundred feet in height. The Ice Patrol, however, states that during its patrol work the highest iceberg observed was about two hundred and fifty feet high, by actual measurement; while by similar measurement the longest berg observed was about a third of a mile in length.

CHAPTER XIV

WAVES OF THE SEA

PERHAPS no one feature of the sea characterizes it so well as its restlessness. The sea is never at rest. Wind and weather furrow its surface with the quick movements of wave and swell; slow-moving but far-reaching ocean currents transport its waters from one region to another; and even in the most sheltered location and in the calmest weather it rises and falls to the throb of the tide-producing forces of sun and moon. This restlessness of the sea is due, obviously, to the extreme mobility of its waters. It is this which permits it to respond readily to any force acting upon it. And the most noticeable manifestation of its restlessness is in the form of waves.

At first glance, a wave moving in a given direction appears to consist in the bodily movement in that direction of a quantity of water deformed into the familiar sinuous outline of crest and trough. But on more careful examination it is found that in reality two distinct movements are involved, the first consisting of the progression of the wave form, and the second consisting of the actual movement of the water particles. These two movements become clear in the motion of a floating object as the wave passes through the water.

Suppose a cork thrown on the surface of a wave-swept body of water. The waves progress continually in one direction, but the cork does not. On casual examination the cork appears merely to bob up and down as crest and trough sweep past it. Closer examination, however, re-

veals the fact that with this vertical motion a horizontal motion is associated, the cork moving a short distance in the direction of wave progression while it is on the crest of the wave, and back again the same distance when it is in its trough. The movement of the cork is the movement of the water particles themselves, while the movement of the wave is the movement through the water of a certain *form* or *arrangement* of the water particles.

Any mass of water disturbed from its condition of rest tends to set up waves. This is a familiar fact illustrated in a variety of ways—by the pebble dropped in the pond, the wind disturbing the surface of the lake, the boat plowing through the water. Waves may thus arise in various ways. Furthermore, the waves produced in different ways are generally different kinds of waves, each having its own laws of behavior. The subject of waves is thus very extensive and also very complex. Here we shall consider only the more important waves of the sea.

The waves arising from the action of wind are the most prominent waves of the sea. The wind never blows with constant velocity, but always in irregular gusts. This subjects the surface of the water to unequal pressures which deform it from a level surface to an undulating one of crest and trough. These latter become more pronounced as the strength of the wind increases, so that in general it may be said, the stronger the wind, the larger the waves.

Now when we speak of the size of a wave, it must be noted that two elements of wave form are involved; namely, the height of the wave and the length of the wave. By the height of the wave is understood the vertical distance from the bottom of the trough to the top of the crest; by the length of the wave is understood the horizontal distance between like phases in two consecutive waves, for example, between two crests or two troughs.

The relation between wind and wave is not a simple one,

since a number of independent factors are involved. Assuming a sufficient depth of water to permit the full development of waves, the more important factors are the duration of the wind; its sweep, or the extent of open water over which it blows; and the strength of the wind. As regards duration of wind, it is obvious that some time must elapse before a wind of given velocity can bring about the maximum wave development of which it is capable. Clearly, too, the time required would depend on the strength of the wind and on the previous condition of the sea with regard to waves. The problem thus is a complicated one, and the investigations with regard to the matter have not advanced sufficiently to permit the formulation of definite relationships. It appears, however, that the time required for a given wind to bring about the maximum wave development is to be measured in hours with perhaps a day or two as the upper limit.

The extent of open water over which the wind blows is known as its fetch. And, within certain limits, the height of the waves brought about by a wind of given velocity depends on the fetch. Thomas Stevenson, an English engineer who investigated this phase of the matter about the middle of the past century, found that with strong winds the height of waves, in feet, was 1½ times the square root of the fetch in nautical miles. Calling h the height of the waves in feet, and f the length of fetch in nautical miles, Stevenson's formula may be written $h = 1.5\sqrt{f}$.

From the above formula, it appears that with the wind blowing from the land the highest waves that may be expected at given distances from the coast are as follows: 10 miles, 5 feet high; 20 miles, 7 feet high; 50 miles, 11 feet high; 100 miles, 15 feet high; 400 miles, 30 feet high; 1,000 miles, 47 feet high. As was stated above, however, Stevenson's simple formula is applicable only within certain limits. For short fetches, say up to 40 miles, this

simple formula makes the heights of the waves less than they actually are, so that a correction term must be introduced. For distances greater than 500 miles the heights of the waves increase more slowly than is demanded by the formula. Indeed, for distances in excess of 500 miles the fetch of the wind may be totally disregarded, for now it is the strength of the wind that determines the height of the waves.

From the observations that have been made in the various oceans, it has been found that the relation between height of wave and strength of wind, after the wind has been blowing for a number of hours, may be expressed as follows: the height of waves, in feet, is equal to the velocity of the wind in miles per hour divided by 2.05. In round numbers, therefore, we may say that for the open sea half the velocity of the wind in miles per hour gives the height of the resulting waves in feet.

With a wind of 60 miles an hour, which the seaman terms a "whole gale," the above formula shows that in the open sea we may expect waves about 30 feet in height. Even with a wind of 80 miles an hour—a hurricane—the resulting waves should be somewhat less than 40 feet. As a matter of fact, with a hurricane the height of the waves may be much less than 40 feet, for the very violence of the wind tends to reduce the height of the waves by decapitating them, blowing the tops of the crests into the troughs. So it frequently happens that with very severe storms the highest waves occur after the wind has begun to subside.

How can we reconcile with the above facts the stories frequently heard of "mountainous seas" or of waves 100 feet or more in height? These stories, often told in good faith, do not claim to be based on actual measurements, but only on estimates. And when a ship, especially a small one, is in the trough of a wave, the oncoming crest of a forty-foot wave towering above the observer unquestion-

ably looks much higher than it actually is. Furthermore, in estimating by eye the height of a wave, the fact that this estimate is generally made when the vessel is riding down the back slope of the preceding wave introduces a factor which makes the apparent height greater than the actual.

How, then, may the heights of waves in the open sea be measured with any degree of precision? Several methods have been employed. A simple method consists in locating on board ship a point from which the crest of the wave just obscures the horizon when the ship is on an even keel in the trough of the wave. The height of the wave is then given by the height of this point above the water line of the ship. With care, a practiced observer can secure fairly accurate results by this method.

Another method makes use of a barometer with a very open scale. Since the atmospheric pressure at any place varies with the elevation, the barometer will indicate a lower pressure when the ship is on the crest of the wave than when it is in its trough. From the observed change in barometric pressure, the difference in elevation between the crest and the trough of the wave can be computed and thus the height of the wave determined.

The movement of a wave decreases very rapidly below the surface of the water, and methods of measuring wave heights based on this fact have been proposed. More recently a photographic method has been used. The apparatus consists of two cameras placed some distance apart on board ship which give simultaneous photographs of the waves. From these photographs the heights of the waves may then be determined.

From the observations on the heights of waves made in the open sea by various observers and by different methods, it appears that waves exceeding 40 feet in height occur only in severe storms and that 50 feet may be taken as the

extreme height of the waves of the sea due to wind. These heights, it should be noted, have reference to the vertical distance between crest and trough of regular waves, and not to the height attained by water particles of intersecting or breaking waves. When two great waves intersect, a peak may be thrust to a height of 60 feet or more. Similarly when a large wave breaks against an object, part of the water composing the wave may shoot considerably above the height of the crest.

It is to the phenomenal heights attained by the waters of a breaking wave that the accounts of waves exceeding 50 feet in height are to be traced. A wave breaking across a ship will sometimes throw water over places 60 or more feet above the water line of the ship. And along the coast there are well-authenticated cases of breaking waves attaining even greater heights. Minots Ledge Lighthouse, on the coast of Massachusetts south of Boston, towers 80 feet above the level of the sea. Occasionally waves break over the top of this lighthouse. Tillamook Rock Lighthouse offers an even more striking example. This lighthouse stands on a rock about a mile off the coast of Oregon, south of the Columbia River. The lantern of this lighthouse is 130 feet above sea level, yet in severe storms rocks carried by the waves have been hurled through the lantern glass.

Coming now to a consideration of the lengths of ocean waves, we must note first that there is no fixed relation between the height and length of a wave, such that if we know the one we can calculate the other. This arises from the fact, which we shall consider later, that waves vary in form. It has been found, however, that in a general way approximate relationships between length and height may be formulated. Thus, with waves of moderate height, the length is about 30 times the height; with high waves, the length is about 20 times the height; and with very high waves, the length is about 15 times the height. It is to be

emphasized, however, that these are only rough averages, and that wide variations from the figures given may be noted in individual cases.

Various methods may be used for measuring the length of a wave in the open sea. A simple, direct method consists in throwing overboard some floating object attached to a line and paying the line out, until the float is on one crest and the ship on another. The length of the line then gives immediately the length of the wave if the ship is traveling exactly in the same direction as the waves. If not, a knowledge of the angle between the two permits a simple correction to give the true length of the wave.

Another simple method consists in two observers stationing themselves at such points on board a ship that a crest of one wave passes one observer at the same instant that the following crest passes the other observer. If the vessel is running exactly in the same direction as the waves, the length of the wave is clearly the distance between the two observers. If the course of the vessel is at an angle to the wave direction, a simple calculation will give the correct length of the wave. This method, obviously, is applicable only when the length of the ship is not less than that of the waves to be observed.

A more general method consists in noting both the frequency with which the waves overtake the ship and the time required for each wave to run the length of the ship. Thus, suppose that on a vessel 500 feet long, steaming exactly in the direction of the waves, it is noted that it takes a wave 15 seconds to run from one end to the other and that the waves overtake the ship every 18 seconds. This means, then, that the ship is only $^{15}/_{18}$ as long as the wave, and hence the length of the wave is $500 \times 18 \div 15 = 600$ feet. In this case, too, if the ship is running at an angle to the wave direction, a knowledge of the angle permits the correct length of the wave to be determined.

Photographic methods also have been used for measuring the lengths of waves in the sea. And in addition to these direct methods, indirect methods may also be used. From the mathematical theory of wave movement, definite relationships have been established between the length, velocity and period of a wave. Thus the length of a wave in feet is equal, in round numbers, to $\frac{1}{5}$ the square of its velocity measured in feet, or to 5 times the square of its period measured in seconds. We shall consider these latter elements of wave movement somewhat later. Here it is sufficient to direct attention to the fact that, by determining either the velocity or period of a wave, we may compute its length.

As a result of the observations made on the length of waves in the open sea, it may be said that waves several hundred feet in length are not at all uncommon. Storm waves of 500 feet and more in length have been frequently measured, and there are trustworthy measurements of waves with a length of 2,500 feet. It is likely, however, that such extraordinarily long waves result from the interaction of several waves in such wise, that one or more intervening crests become obliterated.

As stated above, in the mathematical development of the theory of wave movement, definite relationships between the length, velocity and period of a wave have been established from theoretical considerations. By the velocity of a wave is meant the horizontal distance passed over by a wave in a unit of time, and by the period is meant the time required for a complete wave to pass any fixed point. Both of these elements of wave movement admit of ready determination on board ship.

It is clear that if the ship were at rest and heading exactly in the same direction as that of the wave movement, the velocity of a wave is derived by noting the time required for the crest to pass two points aboard the ship

some distance apart. Thus, if two observers, stationed 150 feet apart on board ship, found that it took the crest of the wave 5 seconds to traverse the distance between them, the velocity of the wave would be 30 feet per second. If we put w for the velocity of the wave, d the distance between the observers, and t the time in seconds taken by the wave to traverse this distance, we derive the formula for this case, $w = \frac{d}{t}$.

If the ship is steaming in the direction of the wave movement, a wave would require more time to pass our two observers than when the ship was at rest for it must now also, in addition, traverse the distance steamed by the ship. We may take account of this in our formula as follows: Let s = the speed of the ship in feet per second; then the actual distance traversed by the wave during the time t is $d + st$. Hence the velocity of the wave is given by the formula $w = (d + st) \div t = \frac{d}{t} + s$. If instead of going in the direction of wave movement the ship is breasting the waves, the formula obviously becomes $w = \frac{d}{t} - s$. And if the course of the vessel makes an angle with the direction of wave movement, a correction may easily be applied.

Since the period of a wave is the time required for two consecutive crests to pass a fixed point, it follows that it is equal to the length of the wave, divided by its velocity. That is, if we designate the period of a wave by p and its length by l we have $p = l \div w$. The period may also be observed directly by noting the time required for two consecutive crests to pass an observer on board ship. If the ship is at rest, the observed time gives directly the period. If the ship is in motion and traveling in the direction of wave movement, the period of the wave is less than the

observed time, but may be deduced by means of a determination of the velocity of the wave from the following considerations.

The velocity of the wave, w, is determined as outlined above. Then, if t is the time in seconds taken by two consecutive crests to pass the observer, and s the speed of the ship (in feet per second), the distance traveled by the wave is clearly its own length plus the distance steamed by the ship during the interval, that is, $l + st$. The velocity of the wave being given by the distance traveled in a unit time, we have $w = (l + st) \div t = \frac{l}{t} + s$. From this $l = t\,(w - s)$ and since the period equals the length of the wave divided by the velocity, we have $p = t\,(w - s) \div w = t - \frac{st}{w}$. If the ship is breasting the waves the formula obviously becomes $p = t + \frac{st}{w}$ and if the ship's course makes an angle with the direction of wave movement, a simple correction can be applied to take account of this.

The relation between the length, velocity, and period of a wave expressed in the formula, $p = l \div w$, was derived from simple considerations. Other formulæ expressing the relations between the various elements of wave movement have been established, but their derivation would lead us too far afield. Thus, the period of a wave may also be expressed in terms of the velocity, alone, as follows, $p = \frac{2\pi}{g}\, w$ in which π is the ratio of the circumference of a circle to its diameter, namely, the incommensurable number 3.14159... and g is the value of the acceleration of gravity. This latter factor varies slightly with latitude but its average value is 32.172 feet per second. From these two

formulæ for the period of a wave, we may now derive formulæ expressing the length of a wave in terms of the period alone or of the velocity alone. For since $p = l \div w$ and $p = \frac{2\pi}{g} w$, we find easily that $l = \frac{2\pi}{g} w^2$ and $l = \frac{g}{2\pi} p^2$. If now we substitute the values of g and π we find that $2\pi \div g = 0.195$ and $g \div 2\pi = 5.120$. Approximately, therefore, we may say that the length of a wave in feet is two-tenths the square of its velocity in feet per second, or 5.1 times the square of its period in seconds.

The last two formulæ derived permit us also to determine the velocity and period of a wave when its length is known. For it is easily found from those formulæ that $w = 2.26\sqrt{l}$ and $p = 0.44\sqrt{l}$. These formulæ we may express approximately by the statements that with regard to wind waves the velocity is 2¼ times the square root of the length, and the period is one-half the square root of the length. With a wave 100 feet in length, therefore, the velocity is 22½ feet per second and the period is 5 seconds; with a wave 400 feet in length the velocity is 45 feet per second and the period 10 seconds, while with a wave of 900 feet in length the velocity is 67½ feet per second and the period 15 seconds. The wind waves of the sea are therefore short-period waves, their periods being generally less than a minute.

The form of a wave in the open sea approximates closely the curve known as a trochoid or prolate cycloid. This curve is traced out by a point on a circle which rolls on a straight line. The form of a trochoid varies therefore with the position of the generating point on the circle. If it is on the circumference of the circle, the curve is the common cycloid with its sharp crests. If the point is in the center of the circle, the curve traced out is a straight line. Hence,

the form of a trochoid may vary from that approximating the cycloid to that approximating the straight line. In Figure 20, a trochoid is illustrated that lies midway between the two limiting forms.

In the figure, the line *A B* represents the undisturbed surface of the water, *C* and *E* are consecutive crests, and *D* an intervening trough. It will be noted that in a trochoidal wave the crest is steeper and narrower than the trough, and that crest and trough are not equally distant from the undisturbed surface of the water. The wave being steeper above sea level than below, the crest rises higher above sea level than the trough falls below it. The height of the

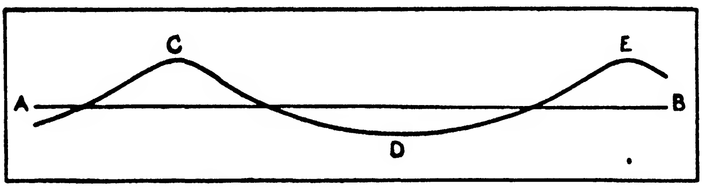

FIG. 20.—PROFILE OF TROCHOIDAL WAVE

crest above sea level varies with height and length of the wave. If h is the height of a wave and l its length, then the height to which the crest rises above sea level is given approximately by the formula $\frac{h}{2} + 0.8\frac{h^2}{l}$. For a wave 500 feet long and 30 feet high the crest of the wave would reach very nearly $16\frac{1}{2}$ feet above sea level, while the trough would fall about $13\frac{1}{2}$ feet below sea level.

Now the different formulæ relating to waves made use of in the preceding paragraphs are based on considerations applying to theoretical trochoids. But the waves of the sea only approximate to the form of the trochoid. It may, therefore, be asked, how well do these formulæ accord with

the facts actually observed at sea? Various investigators have studied waves in the sea and it has been found that there is quite good agreement between the results derived from theory and those derived directly from observation.

While it is primarily the wind that gives rise to the waves of the sea, as soon as the waves arise they are propagated many miles from the spot where they originated. As they move away from the wind-swept region they become gradually lessened in height. And it is in this way that the gentle undulation known as the swell or the ground swell originates.

The swell may also originate in the locality where it occurs, as a result of the gradual dying down of wind waves that the wind had previously set up. In either case, it is a gentle wave movement which in the open sea doesn't trouble the mariner in the least. Along the coast, however, it is sometimes a very troublesome matter. Harbors subject to heavy swells make the docking of a vessel difficult, and a vessel tied up to a dock in such a harbor may be very seriously damaged.

The coast of Morocco facing the Atlantic Ocean furnishes a case in point. Stretching some five hundred miles southwestward from the Strait of Gibraltar, this coastline shows not even a single noteworthy gulf or estuary. The commercial activity of the ports on this stretch of coast is therefore dependent to a large extent on the condition of the sea and particularly on the state of the swell. The ocean swell which makes this coast inhospitable to shipping is felt even in the harbor of Casablanca, protected though it is by large jetties. These swells at times assume such proportions as to cut off communication with the land and seriously damage vessels alongside the wharves and even those at anchor. In January, 1913, a series of large swells paralyzed the commerce of the port of Casablanca

for several months by destroying seven ships and nine laden barges, besides damaging thirteen other barges.

The French naval authorities are charged with the task of maintaining communication with the Moroccan Protectorate and they have found it necessary to give the swell a considerable amount of study. On investigation, it was found that the occurrence of swells on the Moroccan coast could be related to the track of the barometric depressions across the Atlantic Ocean. At Casablanca, for example, analysis proved that the swell was in the majority of cases brought about by a barometric depression between the Azores and Iceland. Various modifying conditions have been discovered for each port but, contrary to what might have been expected, local meteorological conditions are factors of only slight influence.

On the basis of these studies, a service for the prediction of swells was organized in July, 1921, by the Department of Public Works of the Moroccan Protectorate at Rabat. Every day at 8:30 A.M., a telegraphic message is sent to all the Moroccan ports and is also broadcast by wireless, giving the condition of the sea as observed at 7 o'clock and predicting its state for that day and also the following day. At the present time these predictions are about 70 per cent correct; that is, seven out of ten times the predicted swells materialize. The swells which arrive unheralded do not constitute as much as 20 per cent of the observed swells, and are generally not the dangerous swells. These predictions have proved of great value not only to shipping but also to harbor improvement and marine construction.

When a wave from the open sea approaches the coast a change in form takes place as soon as it strikes shallow water. Gradually becoming shorter and higher, and with a constantly steepening front, the crest finally falls over or breaks, producing what is known as the surf. This

change in wave form is due in part to the increased friction of the shallowing bottom, and in part, too, to the decrease in depth of water which reduces the volume of water necessary for maintaining intact the entire wave form.

As a general rule, it may be taken that a wave will break when the depth of the water becomes equal to the height of the wave. But this general rule is subject to modifications brought about by the varying slope and smoothness of the bottom and by such agencies as wind and current. Waves are therefore found at times to break in depths considerably greater than their heights.

If in its onward movement a wave comes against an obstacle tending to arrest its movement, the energy possessed by the wave is exerted against this obstacle. Hence it is against the shore line and structures along the coast that the wave energy is expended. The energy of a wave depends both on its height and its length, and that is why the greatest damage occurs during storms when the waves attain their greatest development. What enormous forces such waves can exert is shown by the ease with which they move large stones weighing many tons.

The destructive force which waves are capable of exerting is well illustrated by the damage done to the breakwater at Wick, Scotland, in 1872 and again in 1877. This breakwater was protected at its seaward end by a large block of cement rubble 45 feet long, 26 feet wide and 11 feet thick, which weighed more than 800 tons. This cement block rested on great blocks of stone bound to it by heavy iron rods, making the entire mass in reality a single block, weighing more than 1,300 tons. In 1872, during a very heavy storm, the entire mass was torn from its foundation by the waves and deposited inside the pier. Later, a much larger mass of concrete was substituted, weighing 2,600 tons; and this, too, was carried away by the waves during a severe storm in 1877.

Where the sea water carries foreign matter either on its surface or in suspension, the normal development of waves under the influence of the wind becomes reduced very markedly. Thus, a stretch of water that carries mud, ice or seaweed will show a much reduced wave movement as compared with a like stretch of clear water. A large school of fish has likewise been known to reduce the wave movement in its immediate vicinity. This decreased wave movement is clearly to be ascribed to the increased friction which the foreign matter introduces, so that part of the wave energy must be consumed in overcoming this friction.

This decrease in wave movement resulting from the presence of foreign matter in the sea is turned to practical account by the mariner, who for ages has used oil to calm the sea. In the familiar expression "oil on troubled waters" we have testimony to the wave-reducing power of oil. The use of oil for this purpose is mentioned by ancient writers, who tell also of the practice of divers carrying oil in their mouths which they released below the surface to reduce wave movement.

In heavy weather, when lowering or hoisting a boat, crossing a bar, towing another vessel, or when breaking waves imperil his ship, the seaman has found that a film of oil spread over the surface of the water has a remarkably calming effect. The action of the oil is of a twofold nature; it appears to prevent the formation of high waves and it also prevents them from breaking. All kinds of oil are not equally efficacious. As a general rule, heavy oils are better than light oils, and animal or vegetable oils better than mineral oils.

It is clear that the calming effect of oil cannot be ascribed to the increased friction that explains the calming effect of such substances as mud, ice or seaweed; for the oil does not penetrate the water but spreads out in a very thin film on the surface. Nor is the explanation that the friction

of the wind on the oil is less than that on water satisfactory, for it is not by its friction that the wind brings about waves. It is in the physical characteristics of the oil film that the explanation lies. The oil film possesses less surface tension than the water and this acts to prevent the breaking of the waves by reducing the steepness of the crests. Furthermore, the viscosity of the oil is greater than that of the water. This acts to reduce quickly and finally to extinguish the small waves that arise, and thus prevents the building up of very large waves.

At times, a vessel will report encountering one or several solitary high waves in otherwise smooth water. Such waves arise not from forces acting on the surface of the sea, as is the case with the wind waves and swells we have been discussing, but from forces acting beneath the sea. Submarine volcanic explosions, seaquakes or any other activities of the earth which result in sudden submarine displacements give rise to movements in the water which find expression at the surface as waves.

The so-called "tidal wave" which at times devastates coastal regions belongs to the latter class of waves. Parenthetically, it may be noted that excepting in name this destructive wave has nothing in common with the tide. As we shall see later, the striking characteristic of the tide is its regularity of occurrence or periodicity, which characteristic arises from the fact that it is brought about by the rhythmically varying tide-producing forces of sun and moon. Because of this periodicity the tide may be predicted years in advance, both as regards time of occurrence and height of water. The tidal wave, however, is in no way due to the tide-producing forces and it does not possess the periodicity characteristic of the tide. In spite of its being a misnomer, the appellation has become so firmly established in the English language that no other general term is used to designate these destructive waves of the sea.

On investigation it is found that two different types of water movement are included under the general name of tidal wave. The first type comprises unusual stages of high water or waves of unusual height brought about by severe storms. These, in reality, are therefore wind waves, or, more accurately, storm waves. Such tidal waves occur at times in coastal regions bordering on shallow waters which are subject to tropical storms of great intensity. Thus the low, flat, densely populated shores facing the Bay of Bengal have been swept again and again by storm waves which have taken a terrible toll of life. It is estimated that more than a hundred thousand people lost their lives in the storm wave that inundated that region in 1876.

It is with this storm wave type of tidal wave, too, that we are familiar on our Gulf coast, and as examples we may cite the storm waves that wrought destruction to Galveston in September, 1900, and to Corpus Christi in September, 1919. In the Corpus Christi storm of 1919 the wind attained a velocity of 80 miles an hour, while in the Galveston storm of 1900 the wind-registering apparatus was blown away when the wind attained a velocity of 100 miles an hour, the greatest velocity of the wind being estimated as 120 miles an hour. The destruction wrought by such storm waves is the result of the combined force of wave, floating wreckage, and wind.

The second type of tidal wave includes all waves that are brought about by seismic disturbances within the earth, such as earthquakes or submarine volcanic outbursts. History records a long list of destructive seismic sea waves, at times attended with appalling loss of life. In the writings of the ancients we find reference to such catastrophes, for example, the destruction of Helice on the shore of the Corinthian Gulf in 373 B.C. In more recent times various coastal regions have been visited by tidal waves arising from seismic disturbances. Among these may be mentioned

the tidal waves that devastated Lisbon in 1755, the region around Krakatoa (Sunda Strait) in 1883, and the coast of Japan in 1896.

Tidal waves accompanying seismic disturbances frequently start with an initial recession of the waters from the coast, which is then followed by the wave that inundates the shore. This appears to arise from the subsidence of some part of the ocean floor not far from the coast affected. If a seaquake is accompanied by the subsidence of an area of the sea bottom it is clear that a movement of the waters toward this area must take place. If this depressed area occurs at a moderate distance from the coast there will be an initial recession of the water from the shore, which is then followed by the inundating wave. However, if the depressed area is close to the coast the waters from the open sea may completely overwhelm the incipient retreat of the water from the shore, so that no initial recession of water will be noted in this case.

Tidal waves may also be brought about by seaquakes at a considerable distance from the shores affected. Thus in February, 1923, Hawaii experienced a tidal wave which apparently resulted from a seaquake that occurred off the coast of Kamchatka, about 2,500 miles to the northwestward. In such cases it appears that a wave from the region of the quake is propagated in a particular direction and that the coast lying in the path of this directed wave will experience a tidal wave.

The heights attained by tidal waves along the coasts which they sweep vary greatly. The tidal wave following the Lisbon earthquake is estimated to have attained a height of fifty feet; that following the eruption of Krakatoa attained on the coast of Java a height of one hundred feet or more. Such large tidal waves frequently carry ships, that happen to lie in the harbors affected, considerable distances inland. Thus the tidal wave following the Krakatoa

eruption carried a gunboat two miles inland in Sumatra and left it stranded thirty feet above sea level.

The waves resulting from seismic disturbances may travel many miles across the sea. The seismic sea waves accompanying the eruption of Krakatoa traveled from the Indian Ocean into the Pacific and across the wide expanse of the latter to the west coast of America, a distance of about ten thousand miles. After traversing such distances the amplitude of the tidal wave becomes much reduced, but its advent at any place is generally well marked on the records of water stage registers, as, for example, on the automatic tide records. Figure 21 represents on a reduced scale the record traced by a tide gauge in San Francisco Bay during the three days August 26-28, 1883.

It should perhaps be noted in passing that a tide gauge consists essentially of some object floating on the water, which is connected by suitable means with a pencil moving up and down a sheet of paper that is driven forward at a uniform rate. To eliminate the excessive motion to which the float would be subject if exposed, it is customary to confine it within a float-well to which the water has access through a small opening well below the surface of the sea. This arrangement eliminates from the float-well waves of very short period and gives to the record of an automatic tide gauge a much smoother appearance than if the float had not been confined within a float-well, in which case it would have responded also to the short-period waves present.

In Figure 21 the upper curve pictures the rise and fall of the surface of the sea within San Francisco Harbor for the whole day of August 26, 1883. In this connection it is convenient to use the twenty-four system of marking the hours of the day. The rhythmic rise and fall with two low waters and two high waters shown by the curve for that day is the tidal rise and fall. That waves of one kind

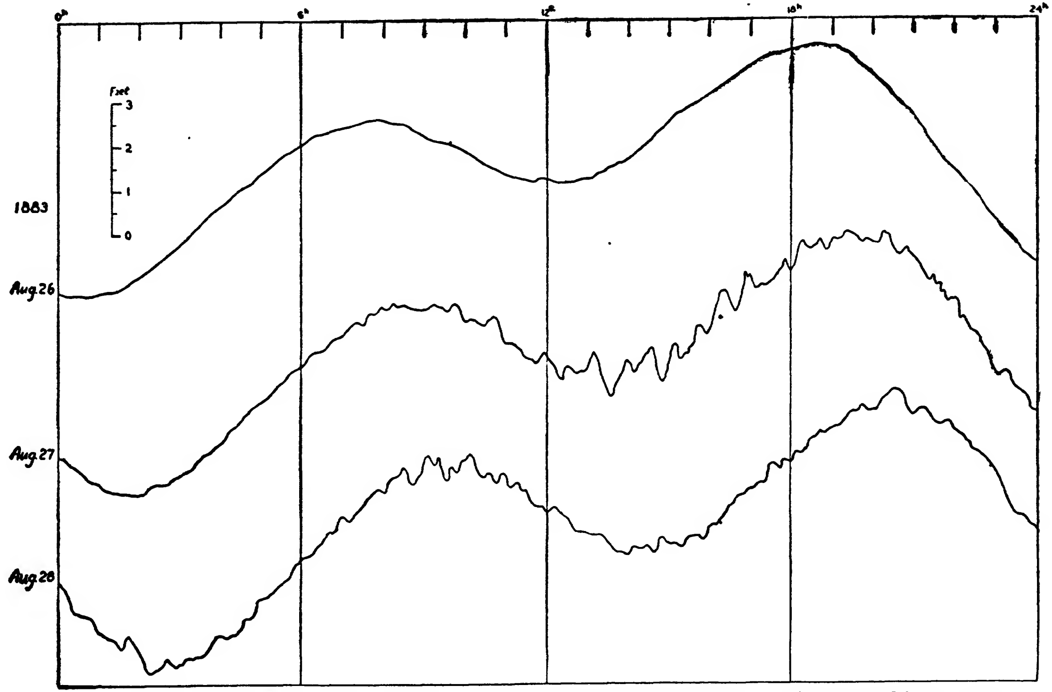

FIG. 21.—RISE AND FALL OF THE SEA IN SAN FRANCISCO BAY, AUGUST, 26-28, 1883

or another were also present is indicated by the fact that the curve is not altogether smooth. But on the whole it is a fairly regular curve.

On the following day, the 27th, the middle curve shows a similar curve for the first seven hours, but after that time the record gives evidence that the tidal rise and fall is being disturbed by waves which from 12 to 18 o'clock (noon to 6 P.M.) have a range of very nearly a foot, and a period of about three-quarters of an hour. Thereafter, this oscillation dies down very gradually, the wave motion still evident on the 28th being on a much reduced scale. The day previous witnessed the eruption of Krakatoa and there is reason to believe that it is the wave generated by this eruption that made itself felt on the tide record of San Francisco Bay.

In its movement across the open sea, the seismic sea wave behaves quite differently from the wind waves or swells. The velocity of the latter, it will be recalled, depends on its length and is altogether independent of the depth of water. The velocity of the seismic sea wave, on the contrary, depends altogether on the depth, the relation between the two being given by the formula $w = \sqrt{gd}$ in which w is the velocity of the wave, g the acceleration of gravity and d the depth of the water. In depths of 2,000 fathoms, therefore, the velocity of a seismic sea wave is 368 nautical miles per hour.

Figure 21 shows that the oscillations within San Francisco Bay arising from the seismic sea wave have a period of about forty minutes. This period, it must be noted, is not the period of the seismic wave, but is the period of oscillation peculiar to San Francisco Bay itself. The same seismic wave that brought about the oscillations shown for San Francisco Bay also put into oscillation the waters in the harbor of Honolulu, but here the period of the oscillation is thirty minutes.

Such oscillations are known as seiches. And one of the interesting features of this type of wave movement is that no matter what the exciting cause of the seiche may be, its period for any given harbor is constant and peculiar to that harbor. Thus on November 11, 1922, a seaquake occurred off the coast of Chile very nearly five thousand miles from San Francisco and about six thousand miles from Honolulu. About fourteen hours later a seiche began developing in San Francisco Bay with a period of about forty minutes, while fifteen hours after the occurrence of

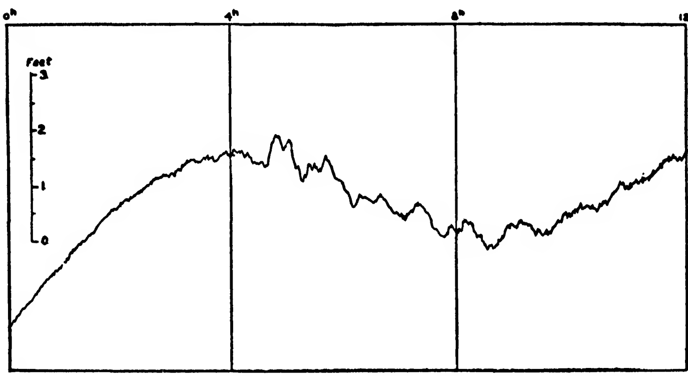

FIG. 22.—TIDE RECORD, SAN FRANCISCO BAY, FORENOON OF NOVEMBER 21, 1910

the seaquake a seiche with a period of about thirty minutes developed in the harbor of Honolulu.

In Figure 22 there is reproduced the tide record from San Francisco Harbor for the forenoon of November 21, 1910. For the first four and a half hours the record is that for the regular rise and fall of the tide with the presence of some of the longer-period wind waves and swells revealed by the small "saw-teeth." After this, the tidal rise and fall is disturbed by an oscillation with a period of about forty minutes, much like that shown in

Figure 21. But in this case the seiche is not caused by a seismic sea wave, but by a sudden change in barometric pressure. On examining the weather record for that day it is found that a striking fluctuation in barometric pressure occurred at San Francisco—a rapid fall of a tenth of an inch from 4 to 5 A.M., and an equally rapid rise of the same amount from 5 to 6 A.M.

It appears, therefore, that the seiche is a wave movement which derives its period of oscillation not from the exciting cause, but from the nature of the body of water in which it becomes manifest. In enclosed bodies of water seiches had been observed and studied for a number of years, the classical work having been done between the years 1870 and 1880 by F. A. Forel, a Swiss physician who studied the seiches on the Lake of Geneva. Forel proved conclusively that in a landlocked body of water the seiche consists of the rocking of the whole body of water about one or more nodal lines. This type of movement is known as a stationary wave, and it will be advantageous to consider this movement in somewhat greater detail before proceeding further.

Suppose we have a rectangular tank, say twenty feet long, filled with water to a depth of about a foot. We may start a wave movement in this tank by agitating the water at one end with a paddle. This wave will progress from one end of the tank to the other in the same way that a wind wave or swell progresses across a body of water, the period of the wave depending on its length, and not on the depth of water in the tank. Such a wave is technically known as a progressive wave.

But we may also set up in our tank of water a wave movement of an entirely different kind by raising and then immediately lowering one end of the tank. The wave movement will now no longer progress from one end to the other. And instead of the water being deformed into

alternate crests and troughs, it will now oscillate or swash about an axis in the middle of the tank as pictured in Figure 23. When motion toward the left ceases the surface of the water will be in the position represented by the line *AB*. The water will then begin its oscillation in the opposite direction, at the end of which the surface assumes the position represented by the line *DE*. The line through the middle of the tank, one point of which is represented by *C*, is the nodal line. As stated before, this type of wave movement is known as a stationary wave.

The stationary wave represented in Figure 23 has one nodal line. It is possible, however, to have stationary-

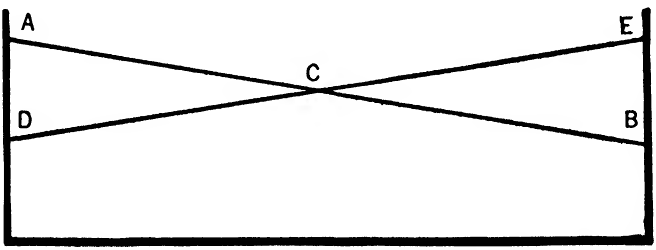

FIG. 23.—STATIONARY WAVE

wave movements with two or more nodal lines. Suppose that two tanks like that in Figure 23 be placed end to end, and stationary-wave oscillations be started in each in such wise that the movements at the contiguous ends coincide exactly. In this case it is clear that the partition walls between the tanks may be removed and the movement sustained in the whole body of water which is now contained in a single tank twice the length of either of the original tanks. In our enlarged tank we now have a stationary-wave movement with two nodal lines; and reasoning of a similar nature will show that a body of water may sustain a stationary-wave movement with three, four or more nodal lines. But in every case we may consider it as made up

of a number of simple stationary-wave movements, each with one nodal line.

The mathematical theory of seiches in enclosed bodies of water was developed to a high degree, at the beginning of the present century, by George Chrystal, an English mathematician, so that now it is possible to calculate with considerable accuracy the period of a seiche in a lake, no matter how irregular in outline, provided the details of its depth and shape are known. The extension of the theory to include bodies of water opening at one end into a much greater basin took place a few years later. In 1908 there appeared, independently, two publications in which this phase of the matter was studied. R. A. Harris, the American tidal mathematician, investigated the matter in connection with his tidal studies. In Japan, Messrs. Honda, Terada, Yoshida, and Isitani attacked the problem in connection with earthquake studies.

These investigations developed the fact that bodies of water opening at one end into larger basins, as exemplified by bays connected with the ocean, are capable of sustaining stationary-wave movements of the kind illustrated in Figure 23, but with this difference; the nodal line, instead of being located in the middle of the body of water, is located at the opening into the larger body. In other words, the seiche in a bay or other body of water open to the sea is exemplified by the movement of the water in half of the tank shown in Figure 23. The theoretical development of the matter showed that the period of a seiche in such a body of water depends on the length of the body of water and its depth, the formula being $p = \frac{4L}{\sqrt{gd}}$, where p is the period of the seiche, L the length of the body of water, and g and d, as before, the acceleration of gravity and the depth of water, respectively. No matter what the exciting cause

of the seiche may be, whether sudden changes in barometric pressure, strong winds, or waves from the sea, the period of the seiche depends not on the period of the exciting cause, but on the length and depth of the body of water.

CHAPTER XV

THE TIDE

To the play of wind and weather the sea responds with the movements of wave and swell. These visibly ruffle the surface of the waters for they are rapid movements, crest and trough following each other in quick succession. But the sea moves also to a slower tempo. Twice each day, in rhythmic fashion, it rises and falls in response to the mighty pulse of the tide-producing forces. These stir the sea to its depths and bring about the phenomena which for short are called the tide.

To an observer out on the open sea the tide is imperceptible because of the slowness of this rise and fall. But along the coast the changing level of the sea manifests itself clearly by its relation to the land. Here it is found that alternately the level of the sea rises for a period of about six hours and then falls for about six hours.

The extent of the rise and fall of the tide at any place is not constant, but varies from day to day. In part, obviously, this variation is brought about by changes in wind and weather. It is a familiar fact that an on-shore wind tends to increase the height of high water, while an off-shore wind tends to lower it. But even a short acquaintance with the tide brings to light a regular variation in the rise and fall which is related to the moon's changing phases. When the moon is full or new the tide rises higher and falls lower than at other times of the month, and when the moon is in her first and third quarters the tide does not rise as high nor fall as low as usual.

Not only in the variations in its height does the tide point to some connection with the moon. The time of the tide, too, unmistakably reveals an intimate relation to the moon's movements. On the average, the moon crosses the meridian of any given place fifty minutes later each day; and the tide likewise, on the average, comes later each day by fifty minutes. Indeed, so clearly does the tide follow the moon that it was for years customary to specify the time of tide at any given place by the interval which marked its following of the moon's passage over the local meridian.

Manifestly, the sun, too, is concerned in the rise and fall of the tide. This is evident from the fact that at times of full and new moon, when sun, moon and earth are approximately in line with each other, the tides have their greatest rise and fall; while when the moon is in her first and third quarters, that is, when sun, moon and earth are at the vertices of a triangle, the rise and fall of the tide is at a minimum. That the tide is brought about by sun and moon must have been recognized early. As we have seen, Pliny in his *Historia Naturalis,* which appeared in the latter half of the first century, definitely ascribed the tide to the action of sun and moon.

How sun and moon brought about the tides remained a mystery for many centuries. Nor was it understood why the moon should be the controlling body. Indeed it was not until the genius of Newton, in the latter decades of the seventeenth century, discovered and formulated the law of gravitation that the connection between moon and tide received a rational explanation.

According to the law of gravitation, the intensity with which the moon (or sun) attracts a particle of matter on the earth varies inversely as the square of the distance between them. For the solid earth as a whole, this distance is obviously to be measured from the center of the earth,

for that is the center of mass of the whole body. But the oceans, which may be considered as lying on the surface of the earth, are on the one side of the earth nearer to the heavenly bodies than is the center of the earth, and on the other side farther away. The attraction of the moon both for the nearer and the farther waters of the sea thus differs in intensity from the attraction for the solid earth as a whole; and it is these differences of attraction that give rise to the forces which cause the ocean waters to move relative to the solid earth. These forces are called the tide-producing forces.

At first thought, it is something of a paradox that in controlling the tidal movement of the sea the sun must yield supremacy to the moon. For the sun is the source of energy and master of life on land and sea. It holds both earth and moon in subjection, compelling them to attend as satellites. In size, too, the moon compared to the sun is altogether insignificant; the sun can furnish material to make twenty-six million moons and still have enough left for something like ten thousand planets the size of our earth. Why is it, then, that the moon plays the leading rôle in the production of the tide, compelling it to keep step with her own movement? What explains this seeming paradox?

The explanation is found in the laws of celestial mechanics. When on the basis of universal gravitation the mathematician works out the law that governs the tide-producing power of a heavenly body, he finds that there are two parts to it. First, the power of a heavenly body to produce tides varies exactly as the amount of matter in the body; the greater the body, the greater the tidal force. Second, the farther away the body, the less the tidal force, but in such manner that when the distance is doubled the tide-producing force is reduced eightfold; or as the mathematician expresses it, the tide-producing power of a heav-

enly body varies directly as its mass and inversely as the cube of its distance.

Applying these laws of the tides to the sun and moon, it would appear at first glance that because of its enormous mass the sun's tide-producing power should be much greater than that of the moon. Indeed, if moon and sun were equally distant from the earth, the sun's tide-producing power would be 26,000,000 times that of the moon. But the moon is 389 times nearer than the sun. According to the second part of the law of tides, therefore, the moon's advantage over the sun because of its nearness is found by cubing 389 which gives, in round numbers, 59,000,000. The moon, therefore, because of its nearness overcomes the advantage of the sun's greater mass in the proportion of 59,000,000 to 26,000,000; that is, the moon's power to produce tides on the earth is something like 2¼ times as great as that of the sun, and hence the tide follows the moon.

The moon moves around the earth in an orbit inclined to the equator. This means that part of the month the moon is north and part of the month she is south of the equator. The orbit of the earth round the sun likewise is inclined to the equator, making the sun part of the year north of the equator and the other part south of the equator. These relative motions of earth, moon and sun, together with the daily rotation of the earth, give rise to two principal classes of tide-producing forces: (1) those having a period of half a day which are therefore called the semidaily forces; (2) those having a period of a day, known as daily forces. Of these two classes, the semidaily forces are the larger. They go through two complete cycles in a day and it is because of the predominance of these semidaily forces that there are at most places two complete tidal cycles, and therefore two high and two low waters in a day.

Now it is important to note that the *tide-producing forces* are astronomic in origin. As a result, they are distributed over the earth in a regular manner, varying only with latitude. Thus, the semidaily tide-producing forces have their greatest intensity at the equator, becoming less toward the poles, while the daily forces are least near the equator and greatest at the poles. But the response of the various seas to these forces is so very profoundly modified by their depth and configuration that the tides as they actually occur differ markedly in many features.

In his tidal theory, Newton simplified the problem by considering the sea to cover the whole earth and to assume at each instant a surface of equilibrium. In other words, he treated the problem as one of water at rest, or as a static problem. By this method of treatment he was able to deduce the principal phenomena of the tides. But after showing that the theory was adequate to account for the tide, Newton did not push his investigations further, leaving the development of the theory of the tides to subsequent investigators.

Newton's theory of the tide furnished the foundation on which all subsequent tidal work is based. But it soon became evident that in its simple form this theory could not be made to explain the strikingly varying features of the tide at different places. And it was at the hands of another famous mathematical astronomer, the Frenchman, Laplace, that the next considerable advance was made. In his great work on celestial mechanics, the *Mécanique Céleste,* he attacked the problem of the tide as one of water in motion, approaching it from the viewpoint of dynamics.

Tidal theory involves difficult mathematical analysis, and so falls outside the scope of the present volume. We may note, however, that in the development of tidal theory it is the mathematicians who have been primarily responsible for its advance. Near the middle of the past century, the

English mathematical astronomer, Airy, attacked the problem as one of water in motion, but treated the tide as the movement of waves in canals, and thereby derived a number of important results. Following Airy, a number of eminent mathematicians have added to the further development of the theory of the tides. As outstanding figures may be mentioned Ferrel and Harris in America; Kelvin, G. H. Darwin, Lamb, Hough, Proudman, and Doodson in England; Lévy and Poincaré in France; Börgen and

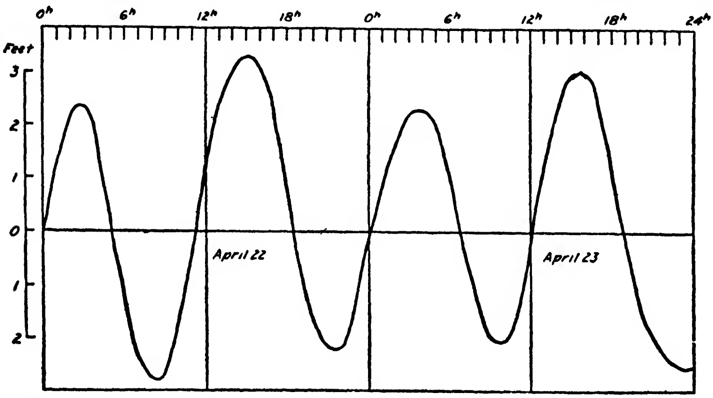

Fig. 24.—Tide Curve, New York Harbor, April 22-23, 1920

Defant in Germany; Sterneck in Austria; Van der Stok in Holland.

Coming now to a consideration of the characteristics of the tides as they manifest themselves in the seven seas, we must note first that in its rise and fall the tide does not move at a uniform rate. From low water the tide begins its rise very slowly, but at a constantly increasing rate for about three hours, when the rate of rise is a maximum. The rise then continues at a constantly decreasing rate for the following three hours, when high water is reached and the rise ceases. The falling tide behaves in a similar manner, the rate of fall being least immediately

after high water but increasing constantly for about three hours when it is a maximum, and then decreasing for a period of three hours when low water is reached. These features are brought out clearly in a graphic representation of the rise and fall of the tide, as in Figure 24.

The horizontal line of Figure 24 represents the undisturbed or mean level of the sea, while the curve represents the varying height of the tide for the two days April 22-23, 1920, in New York Harbor. Such a curve is known as a tide curve, and the clearness with which it visualizes the various characteristics of the rise and fall makes it an extremely valuable means for studying the tide. The varying rate of the rise and fall is immediately apparent from the tide curve. The times and heights of the successive high and low waters are likewise easily determined from the tide curve as is also the range of the tide, by which is meant the difference in height between a high and a low water. It will be noted that the hours of the day are counted in the twenty-four-hour system. This is the more convenient system in tidal work.

From the tide curve of Figure 24 it is seen that the high waters followed each other by approximately twelve and one-half hours, which likewise is the interval separating the successive low waters of the day. If a number of successive high and low waters is observed it is found that this interval varies somewhat, but on the average is 12 hours and 25 minutes. And this is true not only for New York but for most places the world over. This means, that, on the average, the tide becomes later from day to day by 50 minutes, and that the length of the tidal day is 24 hours and 50 minutes.

The tide at any place can be made to give a continuous record of its rise and fall by means of the automatic tide gauge. In principle, this is a very simple instrument. A cylinder that floats on the water is connected by suitable

means with a pencil which moves against a sheet of paper that is driven forward at a uniform rate. As the cylinder rises and falls with the tide the pencil traces a continuous curve of the tide similar to the one in Figure 24, and this furnishes the data for a study of the tide.

The first fact that emerges from a study of the tide at different places is that both the time and the range of the tide vary from place to place. Thus, in New York Harbor the tide is about three hours earlier than at Boston, and is less than half in range, the rise and fall there averaging 4½ feet against 9½ feet at Boston.

Now since the tide follows the moon, the fact that at different places the time of tide is different means that at any given place the tide follows the moon by an interval that is characteristic for that place. For example, with reference to the time of the moon's meridian passage, high water in New York Harbor comes about eight hours after, while at Boston it arrives eleven hours after. This interval by which high water at any place follows the moon's meridian passage is known as the high water lunitidal interval. The fact of a characteristic lunitidal interval for each place has been known for many years and is expressed in the following words by the Venerable Bede who wrote about 1200 years ago: "In every country the moon keeps ever the rule of alliance with the sea which it once for all has agreed upon."

It is to be observed in this connection that the interval by which the tide at any place follows the moon is only approximately constant. It varies somewhat from day to day, in accordance with the position of the moon relative to earth and sun. This variation is not haphazard, but follows strictly regular laws. These laws of variation are different for different places, but a discussion of these would lead us into too great detail.

If we compare the tide curves for different places we

find not only differences in time and range but differences also in the characteristics of the rise and fall. With regard to the latter, tides have been divided into three types, known respectively as semidaily, mixed, and daily types of tide. The semidaily type of tide is illustrated by the tide curve for New York in Figure 24. The distinctive features of this type of tide are two high and two low waters in a tidal day, with but little difference between morning and afternoon tides.

Now compare with the tide curve for New York, the tide

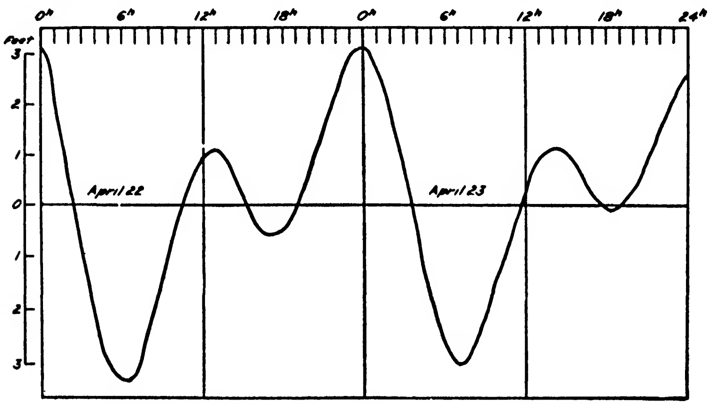

FIG. 25.—TIDE CURVE, SAN DIEGO, CALIFORNIA, APRIL 22-23, 1920

curve for San Diego, California, for the very same days, shown in Figure 25. Here we still have two high and two low waters each tidal day, but morning and afternoon tides are strikingly different. The afternoon tides differ from the morning tides not only in the heights of the high and low waters, but also in the duration of rise and fall. On the morning of April 22, it took about six hours for the tide to fall from high water to low water, while in the afternoon of that day the fall took less than five hours. This type of tide in which two high and two low waters

occur in a tidal day but with marked differences in morning and afternoon tides is called the mixed type of tide. The full significance of the term will become clear a little later.

The mixed type of tide is a most interesting one, for a wide variety of tides are classed under this type. The tide curve for San Diego shown in Figure 25 exhibits differences for both the high waters and the low waters of a day. But at some places the differences occur only in the high waters, while at other places the differences are in the low waters. At Seattle, Washington, for example, the tide is of the mixed type, but here the two high waters of a day differ but little, while the low waters differ greatly. For the same two days of April, 1920, the tide curve for Seattle is shown in Figure 26.

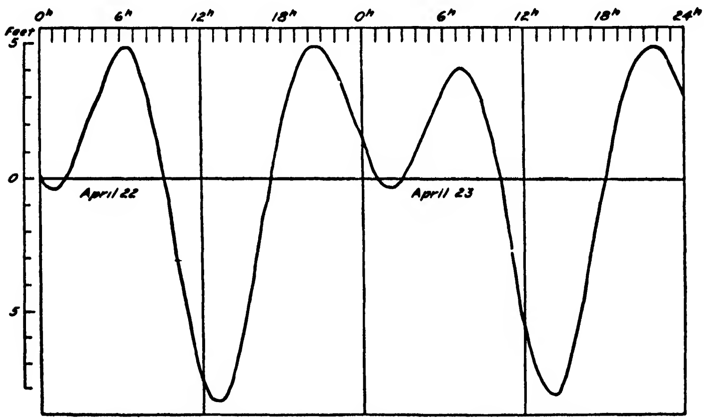

FIG. 26.—TIDE CURVE, SEATTLE, WASHINGTON, APRIL 22-23, 1920

At Seattle for each of the two days shown in Figure 26 the rise and fall averaged 8¾ feet. Morning and afternoon high waters differed but little. The two low waters of each day, however, differed by about eight feet. Although of the mixed type, the tide at Seattle is of a dif-

ferent form from the mixed tide at San Diego, where both high waters and low waters exhibit differences as between morning and afternoon.

Another form of the mixed type of tide is that in which the difference between morning and afternoon tides is exhibited principally by the high waters. This, it is to be noted, represents the reverse condition from that obtaining at Seattle. The tide curve for Honolulu, Hawaii, illustrates this form of the mixed type and is shown in Figure 27, for April 22-23, 1920. For the sake of comparison with the other figures illustrating types of tide, the same days were chosen.

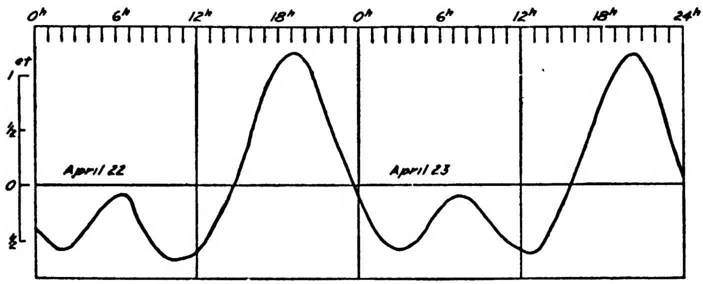

Fig. 27.—Tide Curve, Honolulu, Hawaii, April 22-23, 1920

The tide curve for Honolulu, for the two days shown, brings out clearly that form of the mixed type in which the difference between morning and afternoon tides is exhibited almost wholly in the high waters. It is of interest to note, too, that the morning high waters did not even attain the height of the undisturbed or mean sea level represented by the horizontal line in the figure.

The third type of tide, the daily tide, is in a sense the simplest of all. Its distinguishing feature is the occurrence of but one high water and one low water in each tidal day of 24 hours and 50 minutes. The tide at Pensacola, Florida, is of this type and in Figure 28 is shown

the tide curve for that place for June 1-2, 1926. At first glance it looks very much like the semidaily tide; but whereas in the latter, the rise of the tide as well as the fall takes about six hours, in the daily type, rise and fall each take double the time or about twelve hours.

It must be noted that the differences between morning and afternoon tides at any place are not fixed, but vary from day to day in accordance with the constantly changing declination of the moon, the period of which is approximately 27⅓ days. During this period the difference between morning and afternoon tides is least when the declination of the moon is small and greatest when the

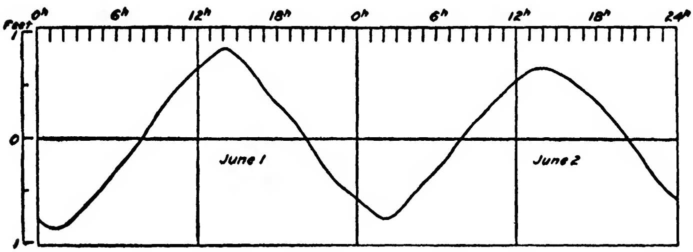

FIG. 28.—TIDE CURVE, PENSACOLA, FLORIDA, JUNE 1-2, 1926

moon's declination is at its maximum. This holds both for the semidaily and for the mixed types of tide.

Without pursuing this phase of the subject in greater detail, it remains to be noted that because of the variation in the morning and afternoon tides due to the moon's changing declination, there are places where the tide is at times of the mixed type and at other times of the daily type. Galveston, Texas, may be cited as an example, the tide curve for June 28-29, 1920, illustrating this feature.

On June 22, 1920, the moon was on the equator, that is, its declination was zero. On that day there was at Galveston but little difference between the morning and afternoon tides. Thereafter, however, with the increasing declination

of the moon, the morning low water decreased in fall daily, while the afternoon high water likewise decreased in rise, so that on the 28th, as shown in the illustration, the difference between the two is only about a tenth of a foot. The following day the morning low water and the afternoon high water merged so that but one high and one low water occurred. On such days, therefore, the tide at Galveston is of the daily type.

To a very large degree, the various oceans may be said to show preferences for one or other of the three types of tide. In the Atlantic Ocean the semidaily tide is the prevailing type, while in the Pacific and Indian oceans the

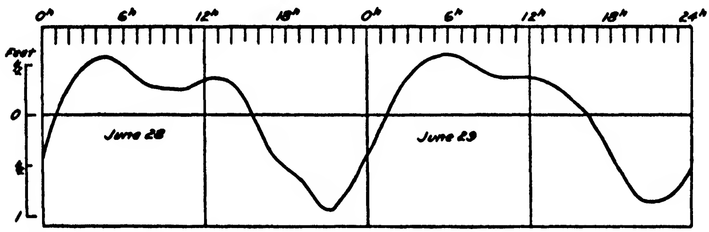

FIG. 29.—TIDE CURVE, GALVESTON, TEXAS, JUNE 28-29, 1920

mixed tide is the prevailing type. The daily tide is found in certain parts of the Gulf of Mexico, the China Sea and in other like bodies of water.

Since the tide-producing forces are of astronomic character, varying over the seas only with latitude, the question arises, why should the different oceans in the same latitude exhibit different types of tide? As a first step in arriving at the answer, it is necessary to see that the mixed type of tide arises from a mixture or combination of the daily and semidaily types. Graphically this can be shown very easily as in Figure 30. Suppose that we have a sea in which the tide is composed of two simple constituent tides, a daily tide and also a semidaily tide. How will the resultant actual tide behave? Obviously, the height of the resultant

tide at any moment will be the sum of the heights of the daily and semidaily tides at that moment. Hence, all we need do to determine the curve of the resultant tide is to add the heights of the constituent tides at various times throughout the day, and draw a smooth curve through these heights.

In Figure 30 the dotted curve represents a semidaily tide, while the dashed curve represents a daily tide. In the present case they are taken as having the same range and having the first high water of each occur at the same instant. When we draw the resultant curve we find it to be the full-line curve of the figure, which proves to be the

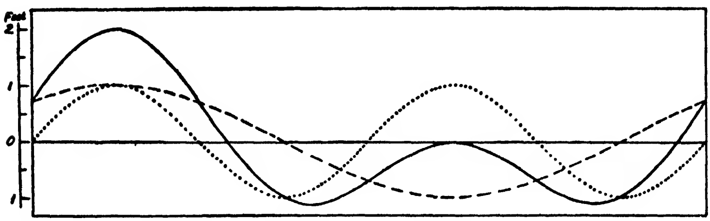

Fig. 30.—Combination of a Daily with a Semidaily Tide

curve of the mixed type of tide with the difference between morning and afternoon tides wholly in the high waters—resembling very closely the tide curve for Honolulu in Figure 27.

Suppose, now, that the two constituent tides still have the same ranges as in the preceding paragraph, but their times are such that the first low water of each occurs at the same instant. The resultant curve will now be quite different. This case will be represented graphically by turning Figure 30 upside down and bearing in mind that time is now reckoned from right to left. The resultant curve now shows the difference between morning and afternoon tides to occur wholly in the low waters, resembling the tide curve for Seattle shown in Figure 26.

It can be shown easily that the different varieties of the mixed tide arise from different combinations of daily and semidaily tides. Thus, the third variety of the mixed tide, in which the difference between morning and afternoon tides was exhibited by both high and low waters, and which is illustrated by the tide at San Diego shown in Figure 25, arises when a daily tide and a semidaily tide of the same range unite so that they are both at mean sea level at the same instant. The mixed type of tide is thus in reality a *mixture,* arising from the combination of the daily and semidaily types. The latter two types are therefore the primary types.

We are therefore led to conclude that the semidaily tide will occur where there is but little daily tide; the daily tide will occur where there is but little semidaily tide, and the mixed type will occur where the two primary types exist together in approximately equal degree. The question regarding the different types of tide now takes a somewhat different form, namely, why should there be varying amounts of daily and semidaily tides in the different oceans?

The answer is found in the laws of wave movement. Suppose we have a rectangular tank partly filled with water. If we raise and then immediately lower one end, a wave will be started which puts into oscillation the whole body of water. It will be noticed that in this wave high water will occur at one end of the tank when it is low water at the other. If we start such waves in tanks of various lengths filled with water to different depths, it will be found that the time taken for a wave to travel from one end of a tank to the other depends only on the length of the tank and the depth of the water. In other words, each body of water has a natural period of oscillation which depends on its length and depth; and from a knowledge of the length and depth of a body

of water its natural period of oscillation can be readily calculated.

Continuing our experiments with the different tanks of water, suppose we now make some arrangement for applying at regular intervals a slight force to the tanks. It will then be found that for any given interval the different tanks respond differently. Some will sustain a vigorous oscillation, others only a moderate oscillation, while some will show very little oscillation. Investigating the matter further, it is found that the greatest rise and fall takes place in those tanks whose natural period of oscillation approximates closest to the period of the applied force, while the rise and fall is least in those tanks whose periods of oscillation differ most from the period of the force.

Applying these laws of wave movement to the tide, it will be recalled that the principal tide-producing forces of sun and moon are of two classes, daily and semidaily. As these tide-producing forces sweep over the various oceans they put the waters in these oceanic basins into oscillation, these oscillations being in part daily and in part semidaily. Now it happens that the lengths and depths of the various parts of the Atlantic Ocean are such as to make their natural periods of oscillation much more nearly half a day than a day. Hence, in this ocean there is little daily tide. In the Pacific and Indian oceans, depths and lengths are such as to permit oscillations of both the daily and semidaily periods. In these oceans, therefore, both daily and semidaily tides are brought about, the combination of the two giving rise to the mixed type of tide characteristic of these oceans. Finally, in the Gulf of Mexico the natural period of oscillation more nearly approximates the daily rather than the semidaily tide, so that here we find the daily tide well developed.

In so far as direct observation of the rise and fall of the tide is concerned, our knowledge of the tide may be said to

be confined almost wholly to the coastline. The difficulties involved in measuring the slow rise and fall of the tide out in the open sea are obvious, and as yet there are no such observations at hand. From theoretical considerations, however, and from observations on the mid-ocean islands which here and there break the wide expanse of the tidally unmeasured sea, it is known that the tide in the open ocean has but a small range—several feet, perhaps.

It is only along the coasts of continental land masses that large ranges of the tide occur. The greatest rise and fall occurs in the Bay of Fundy, the arm of the Atlantic that separates the Canadian province of Nova Scotia from its sister province of New Brunswick and from the State of Maine. At its head the Bay of Fundy forks into two inlets, in the southern one of which, Minas Basin, the tide rises a vertical distance of from forty to fifty feet in a period of six hours and falls the same distance in the following period of six hours.

In part, the increased range of the tide found in coastal waters is due to the fact that in such waters the energy of the tide wave from the open ocean is concentrated into a smaller space, thus producing a greater rise and fall. In certain waterways, as, for example, the Bay of Fundy, it is also due to the fact that length and depth are such that the natural period of oscillation of the waterway approximates the period of the ocean tide. This coöperates with the gradually narrowing channel to produce the very large range of the tide.

The great ports of the world, with relatively few exceptions, are situated on tidal waters. To the deep-draught vessels of modern commerce the rise and fall of the tide in these harbors and in the channels connecting them with the open sea is a matter of importance. For, obviously, places which at high water are of sufficient depth for safe passage may at low stages of the tide be dangerously shoal.

To guide his vessel safely and at the same time maintain the exacting schedules required of present-day commerce, it is necessary that the mariner have at hand advance information of the stage of the tide throughout the region he is to traverse.

This advance knowledge of the state of the tide is furnished by the tide tables for various ports. For any given port a tide table usually presents the information in the form of predicted times and heights of the high and low waters for every day of a calendar year, and is generally issued six months or more in advance of the year for which it is to be used. The importance of tide tables is attested by the fact that each of the leading maritime nations finds it essential to publish annual tide tables for the use of its navy and merchant marine.

The appearance of a modern tide table is illustrated in Figure 31 by a page from the *Tide Tables, United States and Foreign Ports for the Year 1930.* This page gives for the port of Boston, Massachusetts, the predicted times and heights of each high and low water for the last three months of the year 1930, four such pages giving the predictions for the full year. These prediction were made in 1928 and the tide tables containing them were issued early in 1929. Parenthetically, it may be noted that predictions for fifty or one hundred years in advance can be made as easily as two years in advance.

In the tide tables, as the illustration shows, morning and afternoon tides are distinguished by different type, morning tides being indicated by light-faced type, while afternoon tides are indicated by heavy-faced type. The heights of the high and low waters are reckoned from the plane of mean low water, which is the average of all the low waters over a considerable period of time. This plane is likewise the one which is used on the charts of this region, so that the mariner by the aid of his chart and tide table can tell

BOSTON (Commonwealth Pier No. 5), MASS., 1930

Day	OCTOBER				Day	NOVEMBER				Day	DECEMBER			
	High		Low			High		Low			High		Low	
	Time	Ht.	Time	Ht		Time	Ht.	Time	Ht.		Time	Ht.	Time	Ht.
	h. m.	ft.	h. m.	ft		h. m.	ft.	h. m.	ft.		h. m.	ft.	h. m.	ft.
1	6 30	7.2	0 03	1.6	1	7 39	7.8	1 15	1.4	1	7 29	8.3	1 11	1.2
W	**6 44**	**8.2**	**12 18**	**2.5**	Sa	**7 54**	**8.2**	**1 38**	**1.8**	M	**7 51**	**7.9**	**1 42**	**1.1**
2	7 33	7.4	1 08	1.6	2	8 24	8.3	2 02	1.2	2	8 13	8.7	1 57	1.1
Th	**7 44**	**8.4**	**1 21**	**2.3**	Su	**8 40**	**8.4**	**2 26**	**1.3**	Tu	**8 39**	**8.0**	**2 30**	**0.6**
3	8 26	7.8	2 02	1.4	3	9 03	8.8	2 44	0.9	3	8 55	9.2	2 41	0.9
F	**8 35**	**8.0**	**2 15**	**1.9**	M	**9 21**	**8.7**	**3 08**	**0.7**	W	**9 24**	**8.3**	**3 15**	**0.1**
4	9 08	8.3	2 48	1.0	4	9 38	9.3	3 23	0.6	4	9 36	9.6	3 24	0.6
Sa	**9 18**	**9.0**	**3 02**	**1.4**	Tu	**10 00**	**8.9**	**3 40**	**0.1**	Th	**10 06**	**8.4**	**3 59**	**−0.4**
5	9 43	8.8	3 25	0.7	5	10 14	9.8	4 02	0.4	5	10 17	10.0	4 07	0.4
Su	**9 56**	**9.2**	**3 40**	**0.8**	W	**10 38**	**9.1**	**4 27**	**−0.3**	F	**10 53**	**8.6**	**4 43**	**−0.8**
6	10 16	9.2	4 01	0.4	6	10 48	10.1	4 39	0.3	6	10 59	10.4	4 50	0.2
M	**10 31**	**9.4**	**4 18**	**0.4**	Th	**11 15**	**9.2**	**5 07**	**−0.7**	Sa	**11 33**	**8.8**	**5 36**	**−1.1**
7	10 49	9.6	4 36	0.2	7	11 24	10.4	5 18	0.2	7	11 45	10.6	5 35	0.1
Tu	**11 06**	**9.9**	**4 56**	**−0.1**	F	**11 54**	**9.2**	**5 48**	**−0.9**	Su	. . .	. . .	**6 14**	**−1.3**
8	11 21	10.0	5 11	0.1	8	. . .	. . .	5 58	0.2	8	0 18	9.0	6 23	0.0
W	**11 41**	**9.6**	**5 33**	**−0.4**	Sa	**12 02**	**10.5**	**6 30**	**−1.0**	M	**12 33**	**10.9**	**7 03**	**−1.3**
9	11 53	10.2	5 47	0.1	9	0 36	9.0	6 40	0.3	9	1 12	8.9	7 12	0.1
Th	. . .	. . .	**6 12**	**−0.6**	Su	**12 39**	**10.5**	**7 16**	**−0.8**	Tu	**1 22**	**10.5**	**7 52**	**−1.0**
10	0 18	9.5	6 25	0.2	10	1 20	8.8	7 25	0.5	10	2 01	8.8	8 05	0.2
F	**12 28**	**10.3**	**6 52**	**−0.6**	M	**1 30**	**10.3**	**8 05**	**−0.6**	W	**2 13**	**10.2**	**8 44**	**−0.8**
11	0 55	9.3	7 03	0.4	11	2 10	8.6	8 16	0.8	11	2 57	8.8	9 02	0.4
Sa	**1 05**	**10.3**	**7 34**	**−0.4**	Tu	**2 22**	**10.0**	**8 58**	**−0.3**	Th	**3 13**	**9.9**	**9 40**	**−0.6**
12	1 37	8.9	7 44	0.7	12	3 05	8.4	9 13	1.0	12	3 58	8.9	10 02	0.5
Su	**1 47**	**10.1**	**8 21**	**−0.1**	W	**3 21**	**9.6**	**9 58**	**0.0**	F	**4 14**	**9.5**	**10 37**	**−0.3**
13	2 24	8.6	8 31	1.0	13	4 08	8.3	10 17	1.2	13	4 56	9.0	11 06	0.4
M	**2 30**	**9.6**	**9 14**	**0.2**	Th	**4 20**	**9.3**	**10 59**	**0.2**	Sa	**5 18**	**9.1**	**11 36**	**−0.1**
14	3 17	8.2	9 27	1.4	14	5 14	8.4	11 24	1.0	14	5 57	9.2	. . .	. . .
Tu	**3 33**	**9.5**	**10 14**	**0.5**	F	**5 35**	**9.2**	. . .	. . .	Su	**6 24**	**8.8**	**12 10**	**0.3**
15	4 21	8.0	10 31	1.6	15	6 21	8.8	0 02	0.1	15	6 57	9.5	0 34	0.0
W	**4 40**	**9.3**	**11 20**	**0.6**	Sa	**6 44**	**9.3**	**12 30**	**0.7**	M	**7 28**	**8.7**	**1 13**	**0.0**
16	5 31	8.1	11 40	1.4	16	7 22	9.4	1 03	−0.1	16	7 53	9.8	1 31	0.1
Th	**5 53**	**9.3**	. . .	. . .	Su	**7 49**	**9.5**	**1 32**	**0.1**	Tu	**8 29**	**8.7**	**2 11**	**−0.4**
17	6 41	8.5	0 26	0.4	17	8 20	10.0	1 57	−0.4	17	8 47	10.0	2 25	0.1
F	**7 03**	**9.7**	**12 48**	**1.0**	M	**8 48**	**9.7**	**2 33**	**−0.9**	W	**9 25**	**8.8**	**3 07**	**−0.8**
18	7 46	9.2	1 28	−0.1	18	9 12	10.6	2 52	−0.6	18	9 37	10.2	3 16	0.1
Sa	**8 09**	**10.1**	**1 53**	**0.3**	Tu	**9 43**	**9.9**	**3 27**	**−1.2**	Th	**10 16**	**8.8**	**3 56**	**−0.9**
19	8 43	10.0	2 26	−0.6	19	10 00	11.0	3 41	−0.7	19	10 25	10.3	4 05	0.1
Su	**9 08**	**10.5**	**2 51**	**−0.6**	W	**10 23**	**9.9**	**4 16**	**−1.6**	F	**11 03**	**8.8**	**4 45**	**−1.0**
20	9 36	10.7	3 18	−1.0	20	10 46	11.2	4 28	−0.7	20	11 11	10.3	4 52	0.1
M	**10 02**	**10.8**	**3 45**	**−1.3**	Th	**11 21**	**9.8**	**5 03**	**−1.7**	Sa	**11 50**	**8.8**	**5 31**	**−1.0**
21	10 24	11.3	4 07	−1.3	21	11 30	11.1	5 14	−0.5	21	11 56	10.2	5 37	0.2
Tu	**10 51**	**10.9**	**4 35**	**−1.8**	F	. . .	. . .	**5 50**	**−1.9**	Su	. . .	. . .	**6 15**	**−0.9**
22	11 09	11.6	4 53	−1.3	22	0 06	9.6	5 59	−0.2	22	0 38	8.7	6 22	0.3
W	**11 30**	**10.8**	**5 23**	**−2.0**	Sa	**12 14**	**10.8**	**6 34**	**−1.3**	M	**12 40**	**10.0**	**6 58**	**−0.7**
23	11 53	11.6	5 38	−1.1	23	0 50	9.2	6 44	0.2	23	1 15	8.5	7 08	0.5
Th	. . .	. . .	**6 10**	**−2.0**	Su	**12 58**	**10.4**	**7 20**	**−0.9**	Tu	**1 32**	**9.7**	**7 42**	**−0.5**
24	0 25	10.4	6 23	−0.7	24	1 36	8.8	7 29	0.6	24	1 59	8.4	7 53	0.7
F	**12 38**	**11.3**	**6 56**	**−1.5**	M	**1 44**	**9.9**	**8 07**	**−0.4**	W	**2 05**	**9.4**	**8 25**	**−0.2**
25	1 12	9.8	7 09	−0.1	25	2 23	8.3	8 18	1.1	25	2 42	8.3	8 40	0.9
Sa	**1 22**	**10.7**	**7 44**	**−0.9**	Tu	**2 31**	**9.3**	**8 55**	**0.2**	Th	**2 50**	**9.0**	**9 10**	**0.1**
26	2 00	9.1	7 55	0.6	26	3 12	7.9	9 09	1.5	26	3 26	8.2	9 28	1.1
Su	**2 09**	**10.0**	**8 32**	**−0.3**	W	**3 21**	**8.8**	**9 45**	**0.7**	F	**3 35**	**8.0**	**9 56**	**0.5**
27	2 49	8.4	8 45	1.3	27	4 03	7.7	10 02	1.8	27	4 11	8.1	10 17	1.3
M	**2 59**	**9.3**	**9 25**	**0.5**	Th	**4 13**	**8.3**	**10 37**	**1.0**	Sa	**4 23**	**8.3**	**10 42**	**0.8**
28	3 43	7.8	9 38	1.9	28	4 56	7.6	11 00	2.0	28	4 56	8.1	11 09	1.3
Tu	**3 55**	**8.7**	**10 21**	**1.1**	F	**5 09**	**8.0**	**11 30**	**1.3**	Su	**5 13**	**7.9**	**11 36**	**1.0**
29	4 43	7.4	10 38	2.3	29	5 50	7.7	11 56	1.9	29	5 44	8.2	. . .	. . .
W	**4 55**	**8.3**	**11 21**	**1.5**	Sa	**6 05**	**7.8**	. . .	. . .	M	**6 01**	**7.9**	**12 01**	**1.1**
30	5 45	7.3	11 41	2.4	30	6 42	7.9	0 21	1.3	30	6 32	8.4	0 18	1.2
Th	**6 00**	**8.0**	. . .	. . .	Su	**6 59**	**7.8**	**12 51**	**1.6**	Tu	**7 00**	**7.5**	**12 55**	**0.9**
31	6 47	7.5	0 21	1.5						31	7 21	8.7	1 08	1.2
F	**7 00**	**8.9**	**12 42**	**2.3**						W	**7 54**	**7.6**	**1 43**	**0.5**

Time meridian 75° W. Heavy-faced type indicates p. m. tides. Heights are reckoned from mean low water, the datum of soundings on Coast and Geodetic Survey charts.

FIG. 31.—SPECIMEN PAGE, TIDE TABLE FOR BOSTON, OCTOBER-DECEMBER, 1930

the depth of the water at any desired time. The figures with a minus sign before them indicate that the height given is below the plane of reference.

To predict the tides two different methods are used. The older one, technically known as the nonharmonic method, is based on the close relationship existing between the times of high and low water at any given place and the moon's meridian passage. It begins by determining, from tidal observations made at the port for which predictions are desired, the time intervals elapsing between the moon's meridian passage and the occurrence of high and low water. These intervals are subject to periodic variations; but from long series of observations these periodic changes can be determined. And since the astronomer can calculate for many years in advance the times of the moon's meridian passage, the times of high and low water at any place may be predicted by this method as long in advance as may be desired.

The heights of the high and low waters by the nonharmonic method are predicted in a similar manner. From the observations made at the port for which the predictions are desired, the average heights of high and of low water are determined. To these average heights corrections are then applied for the varying positions of sun and moon relative to the earth. And the tide tables produced by this method worked quite satisfactorily for Europe and for the Atlantic coast of the United States where the tide is of the simple semidaily type. But when the nonharmonic method is used for the prediction of tides of a more complex type, such as found on the shores washed by the Pacific and Indian oceans, it necessitates so many corrections as to become prohibitive. When the need for accurate tide tables covering the whole maritime world became pressing, a more powerful method for predicting tides was found in the so-called harmonic method.

In the harmonic method the tide as found in nature is conceived as being made up of a number of simple tides, each of which may be referred to some motion of sun or moon. In other words, for sun and moon as tide-producing agencies this method substitutes a number of simple hypothetical tide-producing bodies which, with respect to the earth, have circular orbits in the plane of the equator. Each of these simple tide-producing bodies is assumed to give rise to a tide of its own kind, and the tide as it actually occurs in nature is thus considered as being made up of a number of simple tides, each of which has a period corresponding to the period of its particular hypothetical tidal body.

Now the periods of revolution of the assumed tidal bodies and hence the periods of the simple constituent tides, are determined once for all from the known relative motions of earth, sun and moon. These periods, being independent of local conditions, are therefore the same all over the earth. What remains to be determined for the various simple constituent tides is their phases and amplitudes, which vary from place to place and which can be determined only from tide observations at each place. The mathematical process by which these phases and amplitudes are disentangled from the tide observations at any place is a very ingenious one known as the harmonic analysis and is due to that versatile British mathematical physicist, William Thomson (later Lord Kelvin), who first proposed it in 1867.

As soon as the period, phase and amplitude of a simple constituent tide is known, it is an easy matter to find the height of the tide due to that constituent at any given future time. Hence, to predict the tide that will actually occur at some future time, it is only necessary to add together the heights of the simple constituent tides at that time. The labor involved in doing this by ordinary methods of computation, however, is so great as to be pro-

hibitive; for to predict the tide at a given port with any pretense at accuracy requires the summation, simultaneously, of between twenty and thirty simple tides. And it was only after Lord Kelvin had devised a machine which mechanically effects the summation of the various constituent tides, that the prediction of tides by the harmonic method was put on a practical basis. Since Kelvin's first tide-predictor, made in 1872, there have been introduced improved tide-predictors. A view of the mechanical tide-predictor used by the U. S. Coast and Geodetic Survey in its prediction of the tides is shown in Figure 32.

In the rise and fall of the tide we have water in motion, and moving water means energy. Over the vast expanse of the ocean, therefore, the tide represents an apparently inexhaustible source of energy. In this connection, distinction must be made between tidal energy and wave energy. The waves and swells that disturb the surface of the sea are not due to the tide, and the energy inherent in these waves, which may be utilized through the medium of wave motors, is not tidal energy.

The various schemes that have been proposed for harnessing the tide may be grouped under four classes or systems: the float system, the tidal current system, the compressed air system and the basin system. The float system is a very simple one. A floating body of considerable weight is lifted by the rising tide, and on the falling tide is made to do work by means of a suitable arrangement of gears and levers. Practically, however, this system is of no value. For not only are there mechanical difficulties in transmitting and transforming the slow motion of the falling body, but the amount of power realized by such a scheme is relatively insignificant.

The tidal-current system and the compressed-air system, likewise, are of limited practical application. In the former system the flow and ebb of the tidal current associated

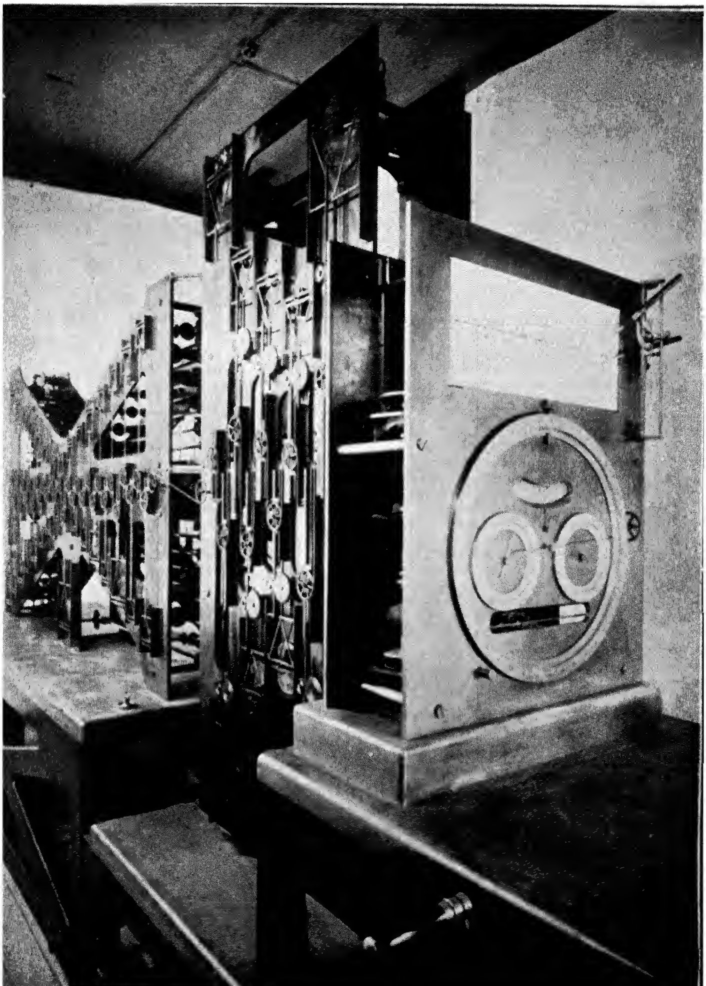

FIG. 32.—UNITED STATES COAST AND GEODETIC SURVEY TIDE PREDICTOR

with the tide is made to rotate one or more paddle wheels installed in a tidal waterway. It is, however, a more efficient system than the float system, but is obviously applicable only to very small power units. The compressed-air system makes use of the energy of the tide in the direct compression of air in closed chambers. It is more efficient than either the float system or the tidal-current system; nevertheless it does not lend itself to large-scale installations.

It is only the basin system that presents the possibility of the practical utilization of the energy of the tides, for this system permits of large-scale projects. In principle, it consists essentially of one or more basins cut off from the sea by dams, in which gates permit the maintenance of differences in the level of the water between basin and sea or between one basin and another. These differences in head of water are utilized for the production of power through turbines and auxiliary machinery.

The amount of power available obviously depends both on the range of the tide and on the area of impounded waters. The appropriate formula can be easily derived. Let the range of the tide in feet be represented by R and the area of the basin in square miles by A. In passing, it may be noted that there are 27,878,400 square feet in a square mile. Let it now be assumed that at low water the gates are closed and remain closed during the entire period of the succeeding rise of the tide. At the time of high water outside, there is, therefore, a difference in head between the level of the water in the basin and the water outside equal to R feet. If the gates now be opened, and if they be assumed large enough to permit the basin to be filled in a few minutes, a mass of water equal to 27,878,400 AR cubic feet have passed into the basin, the average distance of fall of the whole mass of water being obviously $\frac{1}{2}$ R feet.

The weight of a cubic foot of sea water is approximately 64 pounds; hence the amount of work the mass of water flowing into the basin is theoretically capable of doing is $27{,}878{,}400 \times 64\ AR \times \frac{1}{2}\ R = 892{,}108{,}800\ AR^2$ foot pounds. But this represents the work for the total period of the rise which is $6\frac{1}{4}$ hours. Therefore, the horse power theoretically available is

$$892{,}108{,}800\ AR^2 \div (6.25 \times 60 \times 33{,}000) = 72\ AR^2.$$

The formula derived shows that while the power available depends on both the range of the tide and the area of basin enclosed, the range of the tide is the more important factor. For while the power increases simply as the area of the basin increases, in the case of the range the increase is as the square of the range. In other words, as between two regions, one having a tidal range of five feet and the other a tidal range of twenty feet, the tidal power available for each unit area of basin in the latter region is 4×4 or 16 times greater than in the former region.

Theoretically, the tidal power available per square mile of impounded basin is rather large, even for moderate ranges of the tide. In a region where the range of the tide is but five feet our formula shows that each square mile of tidal water impounded is theoretically capable of producing 1,800 horse power; and where the range is as much as twenty feet the horse power available, *theoretically,* is 28,800 for each square mile of impounded basin. Practically, however, only a fraction of this power can be obtained.

Certain difficulties are inherent in the problem of the development of tidal power. The tidal day is 24 hours and 50 minutes in length, making the times of high and low water each day successively later. Furthermore, there is the variation in range from day to day, which means variability in power output from day to day. In a small way the energy of the tide has been utilized at various

places, and large-scale developments have been discussed in the past few years. The successful harnessing of the tide is altogether a question of relative cost. With the gradual exhaustion of coal and oil, there can be little doubt that tidal power will become of great importance, unless other sources of power become available.

Brief mention must be made of the tide as agent of geologic change. Along the coast the foreshore is the scene of constant warfare between land and sea. In the actual wearing away of the land, the work is done by wave and current, but it is to the tide that these agencies owe their wide sphere of activity which extends over the zone from low water to high water. And though but little friction attends the movement of the tide, nevertheless it has been of very considerable importance in the evolution of earth and moon. This matter, however, it will be of advantage to take up in a later chapter.

CHAPTER XVI

TIDAL CURRENTS

The waters of the ocean respond to the tide-producing forces of sun and moon not only with the vertical rise and fall of the tide discussed in the preceding chapter, but also with a horizontal forward and backward movement known as the tidal current. These two movements are intimately related, being merely different phases of the single phenomenon of the response of the waters to the tide-producing forces. And it is only for convenience that they are discussed separately.

That the tidal rise and fall of the ocean waters should be accompanied by the horizontal forward and backward movement of the tidal current becomes evident from a detailed study of the nature of the tidal movement. But it is obvious, also, from general considerations. For, taking any point along the coast, it is clear that between the times of low water and high water a mass of water has been transported toward the coast, necessitating a current from the sea or the so-called flood current. Similarly, between the times of high water and low water a mass of water has been transported from the coast, which means a current seaward, or the ebb current.

In navigation the vertical rise and fall of the tide is of importance near the coast or in areas of shoal water. Out in the open sea, however, the navigator is sure of sufficient depth so that he may disregard entirely the tidal rise and fall; but the horizontal movement of the water—the current—now becomes a matter of importance. Hence, the

mariner frequently speaks of the tide when it is the tidal current that he has in mind; as when he says, "a strong tide was encountered."

It is important, however, to distinguish clearly between tide and tidal current, for the relation between the two is not everywhere the same. At one place a strong current may accompany a tide having a moderate rise and fall, while at another place a like rise and fall may accompany a very weak current. Moreover, the time relations between current and tide at different places vary widely. For the sake of clearness, therefore, *tide* should be used in reference to the vertical movement of the water, and *current* in reference to the horizontal movement.

Tidal currents must, furthermore, be distinguished from nontidal currents. In brooks and rivers we are familiar with a current that carries the water from the land to the sea. This current is always in the one direction—seaward—and is due wholly to gravity and not to the tide-producing forces. Winds blowing steadily for a number of hours over extended bodies of water also give rise to currents; but these currents likewise do not arise from tidal causes and therefore do not partake of the characteristics of tidal currents. In the open sea there are great streams—rivers in the sea—like the Gulf Stream in the Atlantic and the Kuro Siwo in the Pacific, which form part of the system of oceanic circulation. But these great currents, too, being brought about by nontidal agencies belong to the class of nontidal currents.

It is to be observed, however, that tidal and nontidal currents generally occur together, the actual current experienced at any place being the resultant of the interaction of the two classes of currents. In some places tidal currents predominate and in others nontidal currents predominate. In the open sea tidal currents are generally very weak; along the coast they become more noticeable,

and in narrow entrances to bays and rivers they frequently attain considerable velocity. It is, therefore, of advantage to begin the study of tidal currents with their characteristics as manifested in the entrance to a bay, choosing for this purpose the Narrows, the entrance to New York Harbor.

There are a number of methods for measuring the velocity and direction of currents, one of the simplest being by means of a current pole and log line. The current pole is an ordinary pole about fifteen feet long and about two inches in diameter. At one end it is weighted with sufficient sheet lead to submerge in the water all but one foot of its length, and to this upper foot is attached a graduated line—the so-called log line. The log line is graduated, so that if the pole is allowed to be carried out by the current for a period of one minute it will give the velocity of the current in nautical miles per hour or, as it is technically known, in knots.

Suppose that at regular intervals, say every fifteen minutes, on the 10th of August, 1922, we had observed the current in the Narrows from an anchored boat, using the log line and pole for measuring the velocities. Our observations would show alternate periods of flood and ebb, each of about six hours' duration. During any one flood or ebb period the velocity is not constant, but varies from zero to a maximum and back to zero again. We can visualize the matter by making a diagram of the observed velocities, plotting the flood current above the line of zero velocity and the ebb current below, and drawing a curve through the plotted points as in the upper curve of Figure 33.

For comparison with the current curve there is shown, by the lower curve of Figure 33, the tide curve in the Narrows for the same day. A glance at the two curves shows how closely the current curve resembles the tide curve. Corresponding to the high and low water of the tide

curve, we have the strength of the current. For the flood this is known as the strength of flood and for ebb, as the strength of ebb. For the current, too, there is a term to designate that instant when the change from flood to ebb (or vice versa) takes place. This instant, during which the velocity of the current is zero, is known as the slack of the current.

If we should continue our current observations in the Narrows we would find that, like the tide, the current varies

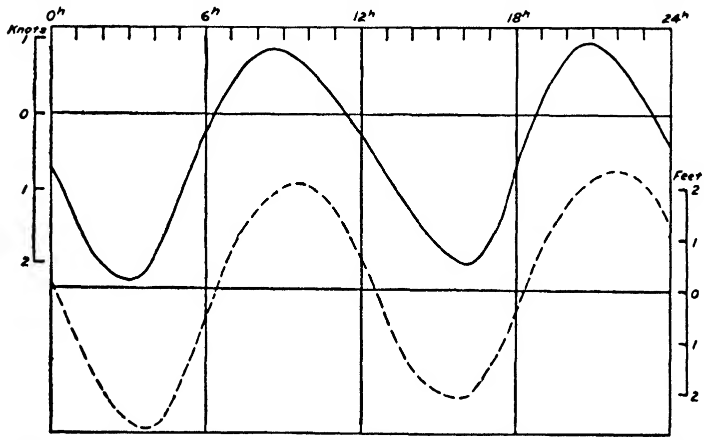

Fig. 33.—Tidal Current, The Narrows, New York Harbor, August 10, 1922

from day to day, this variation following closely the like variation in the rise and fall of the tide. Thus, at times of full moon and new moon, when the rise and fall of the tide is greater than usual, the current likewise is stronger than usual. And at the times of the moon's first and third quarters, when the rise and fall of the tide is less than the average, the velocity of the current, too, is less than the average.

It must be borne in mind, however, that while with regard to any one place it is correct to say "large tides,

strong currents; small tides, weak currents,'' it is true only as a local rule. For it does not at all follow that of two places having different ranges of tide, the larger range is accompanied by the stronger current. Many examples might be cited. Thus, in the entrance to Boston Harbor the rise and fall of the tide is very nearly 10 feet on the average, while the velocity of the current at strength is about 2 knots; in the entrance to Long Island Sound the rise and fall of the tide is but $2\frac{1}{2}$ feet, yet the velocity of the current is $3\frac{1}{2}$ knots. In other words, while tide and current are intimately related, the velocity of the current at any point does not depend on the range of the tide at that point but on the amount of water that must flow past a unit area of the channel at that point.

The intimate relationship between current and tide is further exemplified in type of current. Corresponding to the three types of tide there are the semidaily, daily and mixed types of currents. In Figure 33 the current curve for the Narrows may be taken as representative of the semidaily type. This is characterized by morning and afternoon currents which resemble each other closely. This is the type of current that is associated with the semidaily type of tide and is the usual type in the Atlantic Ocean.

The mixed type of current, like the mixed type of tide, is found in the Pacific and Indian oceans. In this type morning and afternoon currents, instead of being much alike, exhibit differences both as regards velocity and duration of flood and ebb periods. It must be mentioned, however, that as a general rule the difference between morning and afternoon currents at any place is less than the difference between the corresponding tides. The reason for this, while well understood, would involve a detailed treatment of currents and hence cannot be discussed here.

With a current pole we get the movement of the surface waters only, and the question naturally arises as to what

takes place in the deeper layers of the water. Or, looking at it from another point of view, the question may be asked, to what depth does tidal action extend? To answer this question we must have some means for measuring the velocity of the current below the surface. The instrument known as the current meter permits us to do this readily. Various forms of this instrument are in use. One of the simplest forms consists of six cups equally spaced in a horizontal plane that rotates on a vertical axis so that they can respond only to motion in a horizontal plane. In action the meter is connected with a battery and with an ordinary telephone receiver. When the meter is lowered to any desired depth, the moving water impinging on the cups causes them to revolve and each complete revolution is indicated to the observer by a tick in the telephone receiver. The current meter is calibrated so that one revolution corresponds to a definite velocity of the current. Hence, the number of ticks in a given interval of time give directly the velocity of the water, and thus the current at any desired depth can be determined.

With the current meter, observations have been made at various depths in tidal waterways. And without going into detail it may be said that the tidal movement extends from the surface to the very bottom, the velocity being practically the same, except as modified by wind or nontidal currents. As we shall see later, winds give rise to currents; but as a rule these are confined to the surface layers. Similarly, the drainage waters carried out to the sea by tidal rivers give rise to currents. And these, too, as a rule tend to be surface currents. Where such currents coexist with the tidal currents they modify the latter; but since nontidal currents tend to remain surface currents they bring about somewhat different conditions through the various layers of a tidal waterway. It is not difficult, however, to separate from the observations the effects of

the nontidal currents, and when this is done it is found that from top to bottom the tidal movement in a tidal waterway is practically the same.

It is obvious that in the entrance to a bay or river the current is compelled to follow the channel—inland on the flood and seaward on the ebb. Out in the open, however, this restriction no longer obtains, the current having complete freedom so far as direction is concerned. How does the current here behave? If we make current observations at some distance from shore we find that, instead of flowing in one direction for a period of about six hours and in the opposite direction for the following period of six hours as in the entrance to a bay or river, the tidal current offshore changes direction continually.

As an example we may take the observations made on Nantucket Shoals Light Vessel during the afternoon of September 24, 1919. This vessel is anchored about forty miles southeasterly from Nantucket Island. When the current was measured at noon it had a velocity of 1.1 knots and was setting N. 79° E. At one o'clock the velocity was exactly one knot but the direction was now S. 45° E. At each succeeding hour observation showed the current to have shifted still farther to the right, the velocity changing but little. And when the midnight observation was made the current had progressed so far around the compass as to be setting northeasterly again. Currents of this kind are known as rotary currents, while those which set in the one direction during the whole of the flood period and in the opposite direction during the ebb period are known as reversing or rectilinear currents.

It always aids greatly in understanding a phenomenon if we can make a graph of it so that it can be visualized. How can we represent graphically the current at Nantucket Shoals Light Vessel which varies continually in both velocity and direction? Obviously we cannot use the same

scheme as in the case of the current in the entrance to New York Harbor, shown in Figure 33. A procedure that is applicable in this case is to make use of a diagram in which lines radiating from a center give by their lengths

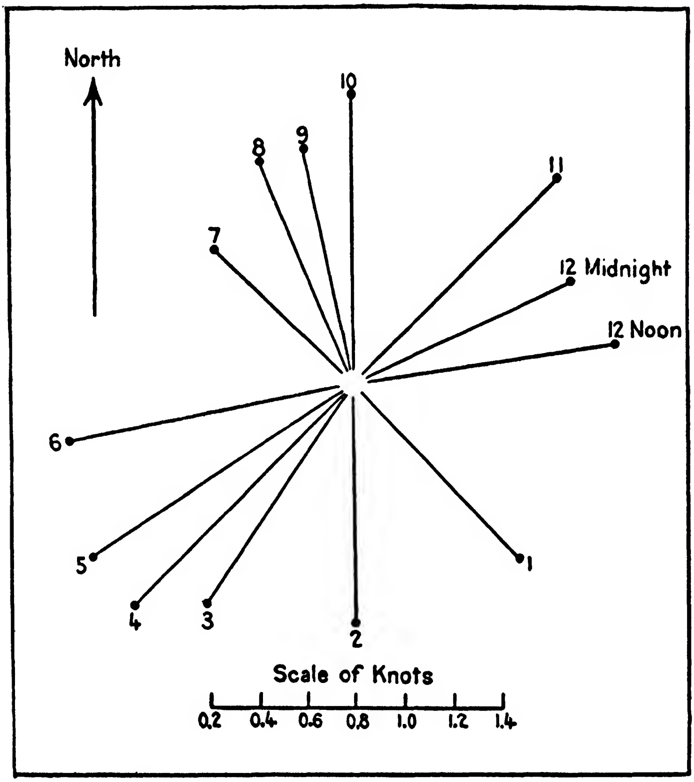

FIG. 34.—CURRENT, NANTUCKET SHOALS LIGHT VESSEL, SEPTEMBER 24, 1919

the velocity of the current and by their directions the direction of the current at the times when the observations were made. Figure 34 gives such a diagram for the currents observed at Nantucket Shoals Light Vessel at the be-

ginning of each hour of the afternoon of September 24, 1919.

To forestall any suggestion that the rotary character of the current shown in Figure 34 may be due to the effect of changing winds, it may be mentioned that there was practically no wind that day at the Light Vessel. Indeed, further observations would only confirm as thoroughly characteristic of the current at this place the features shown in the diagram. No period of slack occurs here, the tidal current at all times running with a velocity of between half a knot and a knot. And there is a progressive change in the direction of the current of approximately 29 degrees per hour, so that in a period of 12 hours and 25 minutes it will have veered completely round the compass.

If we connect the outer ends of the lines in Figure 34 by a continuous curve, a somewhat irregular ellipse results. In large part, the irregularity of this ellipse is due to the fact that the individual observations are subject to slight errors of an accidental nature, since these observations are made on the disturbed surface of the ocean. But if a number of observations are averaged, accidental errors are eliminated as are, likewise, the effects of temporary meteorological disturbances. In the latter case, the current ellipse will present a much more regular outline as shown in Figure 35, which gives the results of continuous hourly observations made on board Nantucket Shoals Light Vessel during the whole month of July, 1920.

The current day does not coincide with the civil day, since like the tidal day it is 24 hours and 50 minutes in length. Like phases of the current do not, therefore, come at the same time each day, but progressively later. Hence, for determining the average hourly direction and velocity of a rotary current, it is necessary to refer it to some phenomenon which has a day of equal length. This can be done easily by reference to the times of high and low water

at some near-by place. For this reason the hourly direction and velocity of the current in Figure 35 is shown with reference to the times of tide at Boston, Massachusetts, H

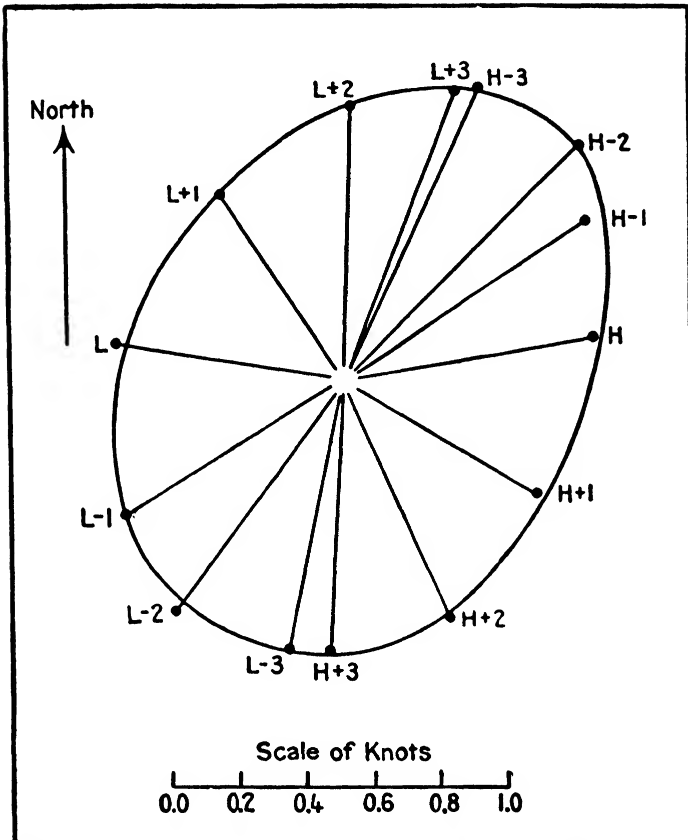

FIG. 35.—MEAN CURRENT CURVE, NANTUCKET SHOALS LIGHT VESSEL, JULY, 1920

standing for the time of high water and L for the time of low water.

The hourly current lines of Figure 35 define a fairly

regular ellipse. The diagram shows that, about two and one-half hours before high water at Boston, the current at Nantucket Shoals has a maximum velocity in a northeasterly direction. For a little more than three hours, thereafter, the velocity of the current decreases regularly, so that about one hour after high water at Boston the current has a minimum velocity in a southeasterly direction. In the following period of about three hours the current experiences an increase in velocity, culminating about two and one-half hours before low water in a maximum velocity in a southwesterly direction. The next period of somewhat more than three hours is one during which the velocity of the current decreases, the minimum coming a little after the time of low water at Boston; and the cycle is then completed by a three-hour period of increasing velocity.

It must be noted that the current curves shown in Figures 34 and 35 represent the current close to the surface. What takes place at some distance below the surface? Observations made at Nantucket Shoals at a depth of one hundred feet below the surface show exactly the same characteristics. Indeed, from the nature of tidal flow it follows that the motion of the waters extends from the top to the bottom.

The current curve of Figure 35 gives the average conditions of the current at Nantucket Shoals. We know, however, that the tide-producing forces vary from day to day in accordance with the changing positions of the moon relative to earth and sun. Rotary currents respond to these variations of the tide-producing forces in the same way as the tides or the reversing tidal currents. At the times of new and full moon the velocity of the current is greater than the average, and at these times the current ellipse would be larger than usual, and when the moon is in its first and third quarters the current ellipse is smaller than the average.

Changes in the declination of the moon, it will be recalled, bring about differences between morning and afternoon tides and currents. In rotary currents this feature presents itself as differences in the current ellipses representing morning and afternoon currents. When the moon is close to the equator, morning and afternoon current ellipses at Nantucket Shoals resemble each other closely; but near the times of the moon's maximum north or south declination, the two ellipses are somewhat different.

We have found that the tide at any point exhibits features in its rise and fall which are characteristic for that place. In the ebb and flow of the reversing current, likewise, each place shows in characteristic features the impress of locality. And this holds true, too, with regard to rotary currents. At different places they exhibit different features. These differences may show themselves in the times of the strength of the current, in the velocities of the current, or in the relation of the major and minor axes of the ellipse, that is, in the flatness of the ellipse. At Nantucket Shoals, as Figure 35 shows, there is but little flattening of the ellipse; at other places, however, the current curve shows a very flat ellipse.

Where there is little difference between morning and afternoon tides, there is as a rule but little difference between morning and afternoon currents. This is the case with the tides and currents in the Atlantic Ocean. And, although the rotary current varies with the changing positions of the moon, a single ellipse represents quite well both morning and afternoon currents, as, for example, Figure 35 for the current at Nantucket Shoals. But when we come to the Pacific Ocean, the differences between morning and afternoon currents are generally so great that a single ellipse cannot well represent both. Here it is necessary to follow the current through the full tidal day of 24 hours and 50 minutes. This is done by referring it to the

tide at some near-by place and distinguishing the lower high waters from the higher high waters, and the lower low waters from the higher low waters. The current ellipse at San Francisco Light Vessel, which is stationed about ten

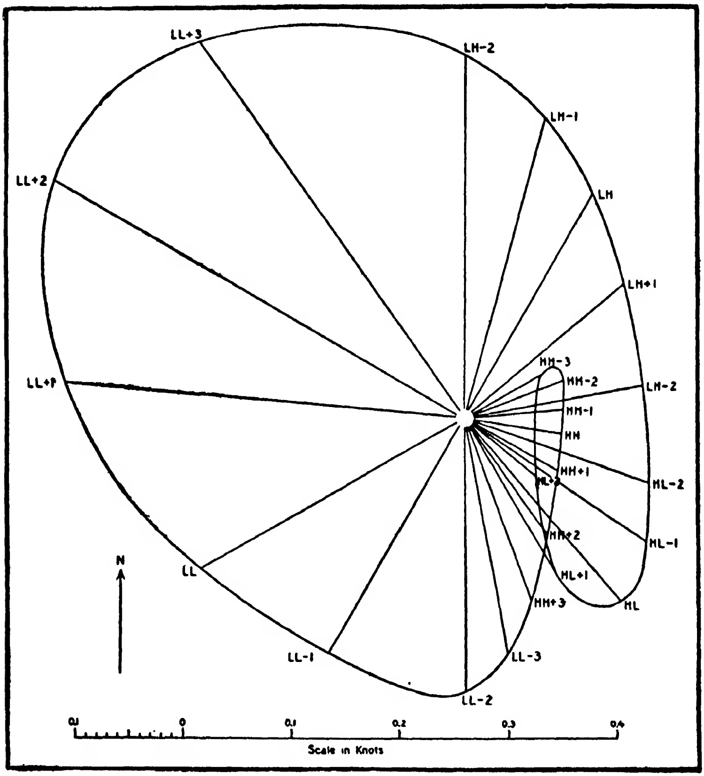

FIG. 36.—MEAN CURRENT CURVE, SAN FRANCISCO LIGHT VESSEL

miles off the entrance to San Francisco Bay, is shown in Figure 36.

In this figure the symbols refer to the time of tide at San Francisco and have the following meanings: *LL* stands

for the time of lower low water, *HL* for the time of higher low water, *LH* for the time of lower high water and *HH* for the time of higher high water. It should be noted that it is the average or mean conditions of the current at San Francisco Light Vessel that Figure 36 represents. When the moon is near its maximum north or south declination, the smaller of the two ellipses vanishes completely and the current requires all day to veer around the compass. At the times when the moon is near the equator, however, the larger ellipse has decreased in size, while the smaller one has increased so that the two ellipses resemble each other.

Along the Pacific coast of the United States the offshore currents are more like those at San Francisco Light Vessel than at Nantucket Shoals Light Vessel. Each place, none the less, exhibits features which are characteristic for that place. It would lead us too far afield, however, to pursue this phase of the subject. Two matters still remain which must be considered now. These relate to the direction of rotation of the current ellipses and to the effects of non-tidal currents.

Examining Figures 35 and 36, it will be noted that the direction of rotation is from north to south by way of east, or clockwise. This is found to be true of the offshore currents all along the Atlantic and Pacific coasts of the United States. It is true, also, of the offshore currents in the northern hemisphere wherever these have been observed. In 1913 the Norwegian oceanographers, Fridtjof Nansen and Bjorn Helland-Hansen, made some current observations on Rockall Bank out in the open Atlantic, some two hundred miles due west of the Hebrides, and the current was found to be rotary, clockwise. While the *Maud* was icebound in the Arctic, not more than a thousand miles from the Pole, H. U. Sverdrup made current observations at various places during the years 1922, 1923 and 1924. At all these

places and at different depths, the current was found to change its direction clockwise.

This clockwise rotation of the offshore tidal current in the northern hemisphere points clearly to the rotation of the earth as the cause. Investigating the question mathematically, Sverdrup arrived at the conclusion that, because of the earth's rotation, the offshore tidal currents should be rotary; furthermore, he found that the direction of rotation should be clockwise in the northern hemisphere and counterclockwise in the southern hemisphere.

In the southern hemisphere there are as yet very few current observations by which Sverdrup's theoretical conclusions may be tested. However, in 1902-03 the *Gauss*, the ship used by the German South-Polar Expedition, was frozen in at a point about sixty miles from the Antarctic continent where the sea was over a thousand feet deep. On measuring the currents here it was found that they were rotary, the direction of rotation being counterclockwise, or from north to south by way of west, quite in consonance with theory.

As a rule, the offshore tidal currents are of very moderate velocity. Consequently, they are likely to be greatly affected by nontidal currents, as, for example, those due to winds. It is clear that the current observed at any place is the resultant of all the currents at the place, tidal and nontidal, that are moving the water at that time. Especially in the case of the rotary currents, the current actually observed at times when strong nontidal currents exist may appear quite different from the simple tidal current, but on examination its presence is clearly revealed. The current at Frying Pan Shoals Light Vessel, which is stationed about twenty miles off the coast of North Carolina, illustrates this nicely.

The undisturbed tidal current at this light vessel is rotary clockwise, the average velocity at strength being

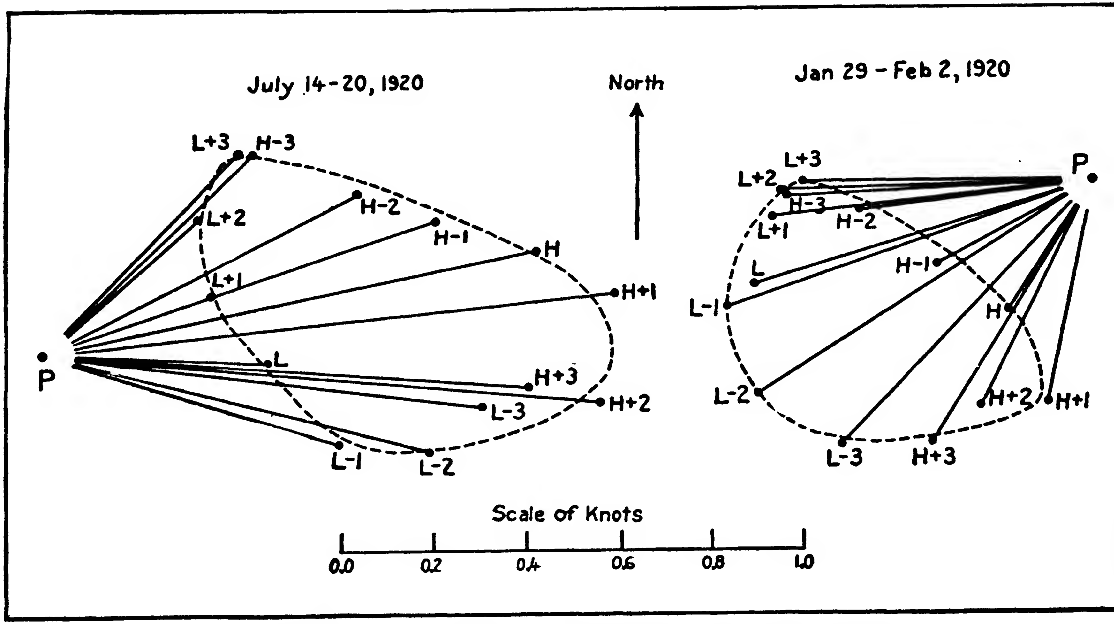

Fig. 37.—Effect of Nontidal Current on Rotary Current

about three-tenths of a knot, the major axis of the ellipse running northwest and southeast. In 1920, from January 29 to February 2, the wind here blew steadily from the northeast with a velocity of thirty miles an hour or more. This wind gave rise to a nontidal current setting southwesterly, which so completely masked the tidal current that at all times during this period the current was observed to be setting southwesterly, as shown in the right-hand diagram of Figure 37. In this diagram the lines from *P* represent by their lengths and directions the velocity and direction of the current at each hour referred to the time of tide at Charleston, South Carolina, *H* standing for the time of high water and *L* for the time of low water. And while the current during this period was setting at all times southwesterly, the plotting brings out the rotary tidal current clearly.

That same year, from the fourteenth to the twentieth of July, the wind at Frying Pan Shoals Light Vessel was blowing from the southwest with a velocity of twenty miles an hour or more. This wind gave rise to a nontidal current which completely masked the rotary tidal current, for the current during this period was observed at all times to set northeasterly. But on plotting the hourly velocities and directions of the current, as before, with reference to the time of tide at Charleston, the rotary character of the tidal current stands out immediately, as shown by the left-hand diagram of Figure 37.

In conclusion, it may be noted that since tidal currents are periodic they may be predicted in the same way as are the tides. In fact, the tide-predicting machine described in the previous chapter is used for predicting the times of the slack and of the strength of the current at places where strong currents of the reversing type exist.

CHAPTER XVII

OCEAN CURRENTS

THE movements of the sea which we considered in the last three chapters—waves, tides, tidal currents—are cyclic movements. In responding to them, the water at any given point moves rhythmically, now up and then down, now forward and then backward. But no permanent change in the location of any of this water is effected by these movements.

There are, however, movements within the sea which transport masses of water continuously in one direction. In responding to these latter movements the waters of the sea suffer permanent change in location. These movements, therefore, are of a progressive nature in contradistinction to the movements of a cyclic nature. To these movements of a progressive nature the name of ocean currents is applied.

Ocean currents are obviously of importance to the navigator. A rapid current may, even in a few hours, carry him considerably off his course. A slow-moving current, however, he may disregard, for its effect on his vessel is so small as to be practically negligible. Hence, the seaman frequently distinguishes between currents and drifts. The former term he restricts to such progressive movements of the waters as have relatively large velocities, while the latter term he applies to slow movements of the ocean waters. Thus he speaks of the Gulf Stream as a current, southward of Cape Hatteras, for here it has a velocity of seventy or more miles per day. Eastward of Newfoundland he speaks

of the continuation of this current as the Gulf Stream Drift, for here the current has a velocity of but ten miles per day.

Within sight of land the movement of a current may be easily detected and measured either from the land or from the sea. From the land, objects floating with the current are seen to change their location. From the sea, a ship wholly at rest in the water will find its location changing with respect to fixed objects on the shore. These observed changes in location furnish the necessary data for determining the velocity and direction of the current. It should be noted, however, that in either case it is the fixed objects on shore which permit the current to be detected and measured.

How may the current out in the open sea be measured? Here, it is clear, there are no means for detecting whether or not the water is moving, for no fixed objects are at hand by which change in location may be noted. If it were practicable to anchor in the open sea, the anchored vessel would constitute a fixed object, with respect to which the current might be observed, or from which the current could be measured by means of current meters. But it is altogether impracticable to anchor in such depths and therefore it is by indirect means that ocean currents are measured as a rule.

A large part of our knowledge of ocean currents is derived from the navigator's log books in which he notes the speed, course steered and position of his ship. In charting the course of his vessel across the trackless sea, the navigator must determine the position of his ship daily. Each day at noon this position is determined by means of astronomical calculations based on observations on the heavenly bodies and noted in the log book.

Now the only reason that it is necessary to make use of astronomical observations and calculations for determining

the position of a ship at sea is that the ship is subject to various disturbing forces, of which currents are usually the most important. Were it not for these disturbing forces, the position of a ship could be determined easily from its speed and course, that is by "dead reckoning." But since the mariner has no means for determining the

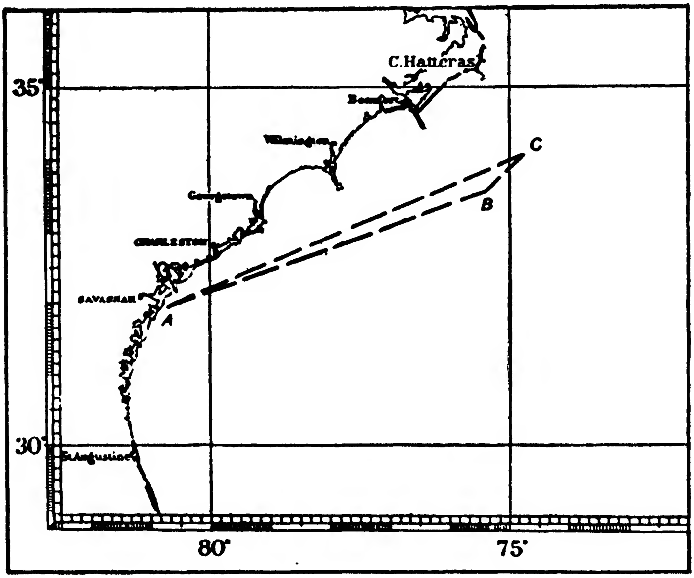

FIG. 38.—DETERMINATION OF CURRENT FROM ASTRONOMIC AND DEAD-RECKONING POSITIONS

direction and velocity of the current to which his vessel is subject, he cannot rely on his dead reckoning position and is compelled to resort to astronomic observations.

If the only disturbing force were the current, the difference between the astronomic and dead-reckoning positions would permit the accurate determination of the velocity and direction of this current, as the following example will make clear. Suppose a vessel is steaming out of Savannah

Harbor bound for Europe, and that at noon it is abreast of Savannah Lightship, the location of which is indicated by point *A*. Suppose that the course of the vessel is N. 70° E., and that it is steaming through the water with a velocity of 12 knots. By dead reckoning it should at noon the following day be $12 \times 24 = 288$ miles N. 70° E. from *A*. On a chart the navigator lays off the line *AB* in the direction N. 70° E. and makes its length equal to 288 miles on the scale of the chart. The point *B* then gives the dead-reckoning position of his ship. But from astronomical observations the position of the ship at noon is determined to be at point *C*, so that the course actually steamed was *AC* instead of *AB*. Clearly, then, a current whose direction is given by the direction of *BC* must have been acting on the ship during the 24 hours. In this example the direction of *BC* is N. 45° E. and its length is 36 nautical miles, so that during the 24 hours between the noon positions, the ship was subject to a current having an average velocity of 1½ knots in a direction N. 45° E.

As mentioned, the difference found between the dead reckoning and astronomic positions cannot be ascribed wholly to the effect of currents. Other agencies, as, for example, the effect of the wind on the vessel, and certain features of the compass, are also responsible. Nevertheless, the current is generally the predominating cause. Moreover, if we average the results obtained over a given stretch of the sea by various vessels, the effects of other causes will very largely balance out, leaving as the net result the effect of the current.

Further information in regard to ocean currents is obtained from objects drifting in the water. Thus, the drift of an iceberg betrays the current which carries it. Similarly, abandoned vessels and wrecks floating in the sea, which are sighted from time to time, furnish information with regard to the currents. But such information must

be very carefully interpreted, otherwise totally contradictory results may be derived. The drift of the American schooner *Fred Taylor* furnishes an illuminating example.

On June 22, 1892, when the *Fred Taylor* was about one hundred miles southeasterly from Nantucket Island, she

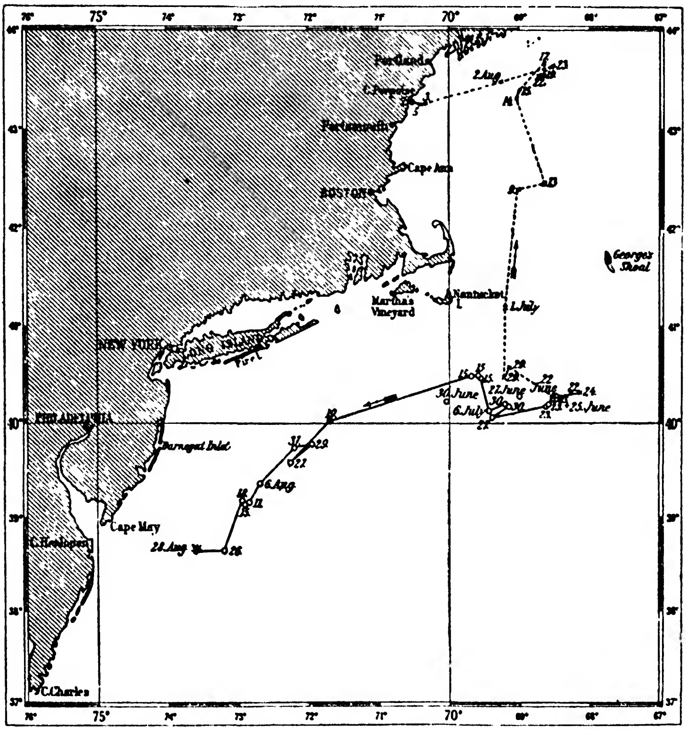

FIG. 39.—DRIFT OF WRECKAGE OF THE "FRED TAYLOR" (AFTER KRÜMMEL)

was run down and cut in two by the steamer *Trave.* The two parts remained afloat, drifting with the wind and current for about two months. But these drifts were in diametrically opposite directions; the stern was carried to the north and finally stranded on the coast of Maine, near

Cape Porpoise, while the bow drifted southwest and finally sank off the entrance to Delaware Bay. The drifts of the two parts are shown in Figure 39, the dotted line representing the drift of the stern and the full line that of the bow.

The position of the *Fred Taylor* when run down is indicated by the circle with enclosed cross. The open circles associated with the full lines show the successive positions of the bow, the figures near these circles giving the dates when sighted at these positions. Similarly, the crosses and figures associated with the dotted lines give the successive positions of the stern and dates when sighted at these positions. The stern stranded near Cape Porpoise on the seventh of August, while the bow sank three weeks later off the entrance to Delaware Bay.

From the drift of the wreckage of the *Fred Taylor*, what can be learned of the current in this region? At first glance apparently nothing, for the two drifts appear to give contradictory results. But on looking into the matter more carefully, it is found that the stern projected considerably out of the water, while the bow was deeply immersed. The wind was prevailingly from the southwest during the period, so that the high projecting stern sailed northerly with the wind. The deeply immersed bow, however, offered no hold for the wind and therefore drifted with the current which was southwesterly. It is interesting to note, too, the impress of the southwesterly current in the drift of the stern, which in spite of the southwesterly winds drifted not northeast but very nearly north.

A further source of information in regard to ocean currents is furnished by the so-called drift-bottles. A drift-bottle is merely a tightly sealed bottle containing a self-addressed card giving the date and place where it was set adrift and requesting that the finder note the date and place where found before forwarding. The drift-bottle is weighted to float with its cork just submerged so that

it will be unaffected by the wind. It has the advantage over the other drifting bodies mentioned, in that it may be set adrift at any desired place.

Obviously, the information given by drift-bottles is of somewhat limited scope. When found, the question of how long a time it may have been in the vicinity remains unanswered. Furthermore, the route followed by the bottle between the points where it was released and found can only be conjectured. However, the advantage of being able to set it adrift at any desired place, together with its small cost, make it a favorite means for deriving data with regard to currents.

On charts which picture the circulation within the sea, we have become accustomed to seeing the currents indicated by arrows which convey an impression of constancy both in velocity and direction. It must be noted, therefore, that when the oceanographer gathers together the information with regard to ocean currents that has been derived from the various sources, he finds that the data do not range themselves in accordance with any easily recognizable and well-defined rules. For any given region of the sea the data appear at first glance contradictory: not only does the velocity appear to be erratic, but what is even more disturbing, the direction likewise appears erratic. Observations for the same region will show the current to have set northerly at one time and southerly at another, and then again easterly and at still another time westerly.

Now there are certain regions in the sea in which the current sets steadily in one direction with but little variation. In the Gulf Stream region, for example, from the Straits of Florida northward for a distance of more than six hundred miles, the current sets northerly except when disturbed by unusual weather conditions. For the sea as a whole, however, such constant currents are the exception and not the rule.

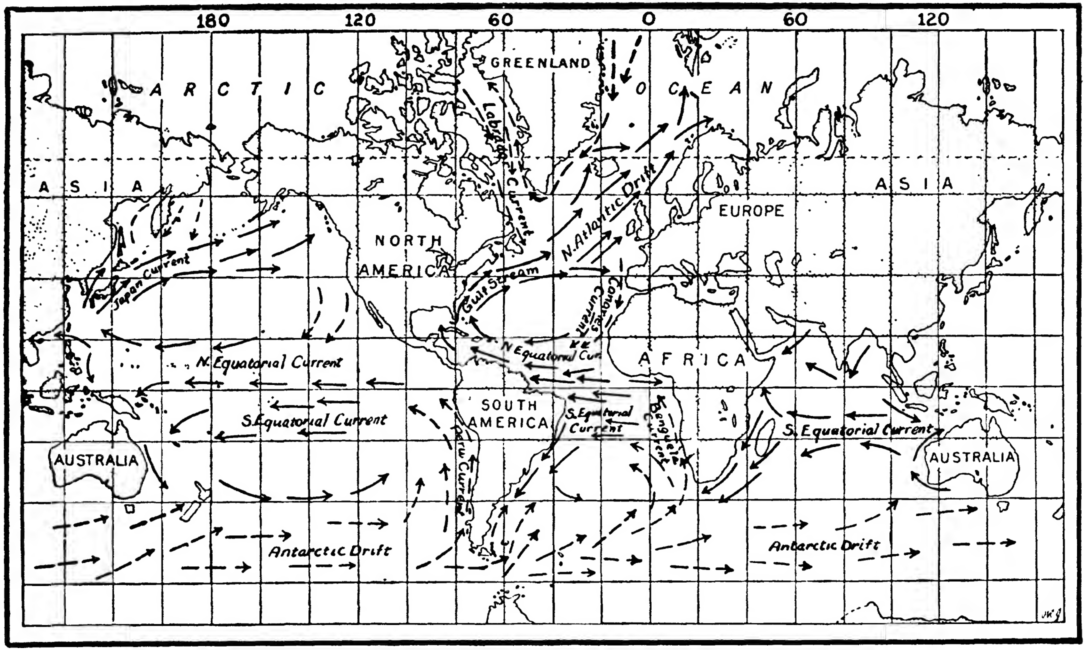

FIG. 40.—MAIN SYSTEMS OF SURFACE CURRENTS OF THE SEA

The apparently irregular behavior of ocean currents gives way to a large measure of order when the results of observations are arranged in accordance with the seasons. In other words, there is an annual variation in ocean currents. On further investigation, too, it is found that at any given point the current will set more often in one direction than in any other. And it is this prevailing or predominating direction that is pictured in our atlases.

A study of the various currents in the different oceans would require so much detail as to fall altogether outside the scope of this publication. The reader interested in this phase of the subject must consult standard atlases and the more formal oceanographic treatises. Here we can notice only the larger features of the oceanic circulation. These larger features are represented in Figure 40.

A glance at Figure 40 shows considerable similarity in the circulation of the three oceans. In the southern half of each ocean the dominant feature is a great whirl, or eddy, moving counterclockwise, lying roughly between the equator and latitude 40° S. In the northern half of each of the oceans there is a similar whirl, but with clockwise movement, extending from the equator to latitude 40° N. Between these two whirls in each ocean there is a narrow belt in which the motion is in the opposite direction. The various components that make up these whirls have been given distinctive names, the more important of these being indicated in the figure. It should be noted, too, that Figure 40 represents the movement of the surface waters only.

It is clear that the water coming from the high latitudes will be cold water, while that coming from the low latitudes will be warm water. In the figure the warm currents are distinguished from the cold currents, the former being indicated by full arrows and the latter by dashed arrows. In the Indian Ocean the different monsoons bring about dif-

ferent current systems, and in the figure it is the currents associated with the northeast monsoon that are shown.

The general scheme of circulation of the surface waters may, therefore, be characterized as follows. In each ocean there is a flow of water from east to west in the equatorial regions. These flows constitute the so-called equatorial currents, which in the northern hemisphere are called the north equatorial currents and in the southern hemisphere, the south equatorial currents. Between the north and south equatorial currents there is a narrow, and weaker, counter-equatorial current flowing toward the east.

In moving westward the equatorial currents are deflected to the right in the northern hemisphere and to the left in the southern hemisphere, so that in latitude 40° they constitute current systems moving toward the east. The great eddies are then completed by currents which flow southerly in the northern hemisphere and northerly in the southern hemisphere and which finally enter into the equatorial currents. To complete the picture we must note further that the eastward-moving component of each great eddy in the northern hemisphere gives rise to a subsidiary current which sets northeasterly, while in the southern hemisphere the great belt of water of the Antarctic Ocean is traversed by an easterly current.

It must be emphasized that it is only with regard to the larger features of the circulation that the current systems in each of the oceans may be described as similar. For in each of the oceanic basins, features of a local nature modify the symmetrical arrangement sketched above. The oceanic basins vary in area and in depth; the configuration of the land boundary is different for the different basins, and wind and weather are not wholly functions of latitude. These differences find reflection in local differences of the oceanic circulation.

The movement of the water in an oceanic current is

generally slow, something like half a mile an hour or even less. But in certain currents it is much faster. The Japan Current, or the Kuro Siwo as it is frequently called, flows at the rate of between two and three miles per hour, and in the Gulf Stream we find velocities of as much as four miles an hour. Furthermore, the various currents are subject to seasonal variations of a periodic nature and to smaller variations also from year to year.

Now to what are ocean currents due? What forces are at work to maintain these slow but mighty movements of the sea? A consideration of the matter brings to light the fact that the circulation of the sea results from the interplay of a number of forces, some of which originate within the sea itself while the others reside outside the sea. Let us consider first the causes originating within the sea.

An ocean basin extends over so wide a range of latitude that its waters are subject to very unequal heating. In the tropics the water is heated most and in the polar regions least. As a result of this the water in the tropic regions is expanded most and in the polar regions least. This brings about a difference of level or a surface gradient from the equator to the poles. Therefore, as a first result of the unequal heating of the waters a force arises that tends to set up a surface current from the equator to the poles.

But this surface current is only the beginning of a series of consequences. The fact that the water in the tropics is warmer than the water in the polar regions means also that it is less dense than the latter water. As soon, therefore, as the current moves the surface waters from the equator to higher latitudes, a difference in pressure results within the depths of the ocean. To equalize this difference of pressure a subsurface current arises which carries the water from the area of greater pressure to that of least pressure, that is, from the polar regions to the tropics.

As a result of the unequal heating of the ocean waters

we therefore find forces that tend to set up surface currents polewards and subsurface currents equatorwards. These, in turn, bring about other currents; for to replace the water flowing away from the tropic regions necessitates a compensating flow upwards from the depths in these regions. Similarly, to compensate for the equatorward flow of the subsurface waters in the polar regions, a downward flow must take place in those regions. It is, therefore, as a closed circuit that we may picture the circulation of the sea arising from the unequal heating of the waters: polewards on the surface, downward in the polar regions, equatorward within the depths, and upwards in the tropics.

Currents are also brought about by differences in salinity, for the more saline the water, the greater the density. Two areas within an ocean basin having the same temperature but different salinities cannot remain in equilibrium. For the pressure within the depths of the more saline waters is greater than that in the less saline, and therefore a subsurface flow takes place from the former to the latter. This tends to give rise to a difference in surface elevation between the two regions and a return current therefore arises on the surface.

Differences in the salinity of sea water result from differences in evaporation, in rainfall, and in the distribution and melting of ice. Any one of these agencies may therefore be regarded as a cause of ocean currents, but it is more convenient to group them all under the single cause of salinity difference. It should, perhaps, be noted that a very prominent rôle in the circulation of the sea has been assigned to ice-melting by the Swedish oceanographer, Otto Pettersson. In the melting of ice not only do differences in salinity arise, but also temperature differences. From a consideration of the changes arising within sea water as a result of ice-melting, and from experiments carried out in the laboratory, Pettersson builds up a most interesting

theory on the widespread influence of ice-melting on oceanic circulation.

Turning now to a consideration of forces outside the sea which may bring about ocean currents, we may note first the effects of variations in atmospheric pressure. In our consideration of the level of the sea it was found that any arm of the sea may be regarded as constituting a huge water barometer, the level of which falls with an increase in the barometric pressure, and rises with a decrease in pressure. If over one region of an ocean basin the atmospheric pressure differs from that in another region, a circulation of the water in that basin must arise. For over the region subject to the greater atmospheric pressure greater pressures prevail within the waters, which results in a flow toward the region of lesser pressure. Indeed, it is by means of such currents that the level of the sea rises and falls in response to variations in barometric pressure. But as soon as the level of the sea in the area of greater pressure falls, a surface current from the region of higher level to that of lower level arises. In this manner differences in atmospheric pressure tend to bring about a complete circulation within an ocean basin—a subsurface current from the area of greater pressure and a return surface current from the area of lesser pressure.

Of all the agencies which bring about ocean currents, the wind is the most obvious and most familiar. On comparing a chart that represents the oceanic circulation with one representing the prevailing wind systems, striking similarities become evident at once. Corresponding to the westerly moving equatorial currents, we find the westerly blowing trade winds; corresponding to the easterly flowing currents in the north temperate latitudes, we find easterly setting winds; and corresponding to the easterly current that circles the Antarctic Ocean, we have the "brave west winds" blowing easterly in that region.

While the general correspondence between the circulation of the air and that of the sea is thus unquestioned, it must be noted that detailed studies of the various ocean currents bring out the fact that the wind is but one of the factors involved. To the seaman, however, the wind has always appealed as the principal cause of ocean currents. And for many years he has taken it for granted that a wind blowing steadily over a wide stretch of water gives rise to a current which sets in the direction of the wind.

In this opinion, that the current brought about by the wind sets in the same direction as the wind, the seaman received support from a mathematical investigation of the question published in 1878 by the German physicist, Karl Zöppritz. From his mathematical investigation Zöppritz was led to conclude that a steadily blowing wind will, through friction, bring about a surface flow in the direction of the wind. This moving surface layer will in turn put into motion in the same direction a lower layer of water until finally (after a very considerable period) the whole mass of water, from top to bottom, will be flowing in the direction of the wind. Furthermore, in this moving mass of water, the equations showed that the velocity would decrease in direct proportion to the distance below the surface.

The conclusions resulting from Zöppritz's analysis of the question were accepted for a number of years, for the mathematics employed was sound and these conclusions, moreover, were in accord with the practical view of the matter. To be sure, in the mathematical investigation of such questions it is generally necessary to make certain simplifying assumptions. It must be noted, too, in passing, that Zöppritz did not include in his equations the deflecting force of the earth's rotation, the assumption undoubtedly being that since the velocities of wind-driven currents were never large, the effect of this deflecting force would be so small that it might be completely disregarded.

It was only at the beginning of the present century that these conclusions were called into question. At this time Nansen was studying the results of his observations on the drift of the ice made nearly a decade before, while the *Fram* was drifting across the polar sea. He was struck by the fact that for any given period of time the ice did not drift in the direction of the wind prevailing during this time but to the right of that direction. He suspected that this deviation of the drift to the right of the wind was due to the deflecting force of the earth's rotation, and thereupon requested the Swedish mathematician, V. W. Ekman, to investigate the question anew.

On introducing into the equations of motion the deflecting force of the earth's rotation, Ekman arrived at the conclusion that in a large body of water of infinite depth the wind would give rise to a current which set in a direction 45 degrees to the right of the wind in the northern hemisphere, and 45 degrees to the left of the wind in the southern hemisphere. Furthermore, this surface current would, in turn, put into motion a lower layer of water, the direction of this lower layer being deflected still further from the direction of the wind (to the right in the northern hemisphere and to the left in the southern) so that the deviation of the wind-driven current from the direction of the wind increases uniformly with the depth. The velocity of this wind-driven current, however, from the formulæ derived by Ekman, decreases very rapidly with the depth —in geometrical progression, in fact—so that at the depth where the direction of the current is directly opposite to the surface current, the velocity is only about 4 per cent that at the surface.

The surprising result that emerges from Ekman's investigation is that the deviation of the wind-driven current from the direction of the wind does not vary with latitude, but is invariably 45 degrees at the surface. And since this

deviation is to the right in the northern hemisphere and to the left in the southern, an abrupt change of 90 degrees is demanded at the equator. But it is to be noted that this result is derived on the assumption of an ocean of infinite depth. The sea, however, is not of infinite depth and this abrupt change of 90 degrees, in Ekman's words, "has, of course, no correspondence with reality." Actually, the angle of deflection would begin to decrease in the neighborhood of the equator and be zero at the equator. In fact, for an ocean of finite depth Ekman's equations show that the angle between the surface current and the wind depends on the depth. In a very shallow ocean his calculations make this angle very small, that is, the current sets nearly in the direction of the wind; but as the depth of the ocean increases, the angle increases and approximates to the value of 45 degrees.

It is obvious that near the coast the direction of the wind-driven current must be very considerably affected by the direction of the coastline. From his mathematical investigation Ekman found this to be the case, his calculations showing that, while the surface currents should still deviate to the right of the wind direction in the northern hemisphere and to the left in the southern, this deviation would vary from 0 to 53 degrees, depending on the angle between the coastline and the direction of the wind. And besides this modifying influence on the surface current, he found further that the coastline modifies very profoundly the subsurface currents.

Excepting, then, the region in the immediate vicinity of the equator, the results derived by Ekman show that the direction of the current due to the wind is independent of latitude. For the velocity of the wind-driven current, however, his equations demand a variation with latitude, the velocity in the open sea varying inversely as the square root of the sine of the latitude. Near the coast other fac-

tors enter and this simple relation becomes modified considerably.

Ekman's results were derived by mathematical analysis from considerations of a theoretical nature. Moreover, to make possible this mathematical analysis, a number of simplifying assumptions somewhat at variance with actual conditions were necessary. The question may, therefore, be raised as to how far these results are applicable to the oceans actually existing? In other words, how far are these results borne out by the currents observed in the sea?

Now, the current flowing past any point in the sea at a given time is the resultant of the currents brought about by the various agencies which we have considered. To determine the current due to wind alone, we must eliminate, in one way or another, the currents due to other causes. To do this and derive results not vitiated by accidental errors or unusual conditions means that a number of observations must be obtained, or in other words systematic current observations.

In the open sea systematic current observations are wholly wanting because of the difficulty and expense involved in anchoring in great depths. Near the coast, however, the light vessels maintained as aids to navigation have served as bases from which current observations over considerable periods of time have been made. These light vessels are generally stationed from five to ten miles from the coast, and, therefore, the currents that are observed from these vessels, specially as regards dirction, are modified considerably by the nearness of the coast. Nevertheless, when these currents are grouped in accordance with the direction of the wind blowing at the time, the deviation of the current from the wind direction is found to be in accordance with Ekman's theory. Thus, from observations made on the light vessels both on the Atlantic and Pacific coasts of the United States a deviation of the wind-driven

current of about twenty degrees from the direction of the wind is brought out.

The current observations made from light vessels are confined to the northern hemisphere, no such observations appearing to have been made in the southern hemisphere. But in 1902-03 while the *Gauss,* the ship used by the German South-Polar Expedition, was frozen in at a point about sixty miles from the Antarctic continent, both wind and current observations were made. When wind and current were correlated the direction of the wind-driven current was found to be to the left of the wind.

While no systematic current observations are at hand for the open sea, we may arrive at the relation of wind to current here by making use of the navigator's log books. We have seen that from the difference between his astronomic and dead-reckoning positions we may derive the current experienced in a given region of the sea. Now by correlating these currents with the winds blowing at the time, we should get results that throw light on the relation of current to wind in the open sea. An investigation of this nature was made by the English meteorologist, C. S. Durst, in 1924 for various regions in each of the three oceans. He used several hundred sets of observations and found that in the northern hemisphere the wind-driven current sets to the right of the wind and in the southern hemisphere to the left of the wind. While this angle of deviation varied, it approximated to 40 degrees.

From general considerations it would appear that the velocity of the current brought about by the wind would depend on the velocity of the wind. This is borne out by the studies made on the relation of wind to current. While the relation of wind velocity to current velocity has been found to differ somewhat at different places, as a general rule it may be taken that the velocity of the surface current produced by a given wind is about one and

a half per cent of the wind velocity. Thus a fifty-mile wind will give rise to a current which at the surface has a velocity of about three-quarters of a mile per hour.

The agencies involved in the circulation of the sea which we have thus far considered are such as are of themselves capable of bringing about currents. Now we must note the operation of other agencies which of themselves are incapable of bringing about ocean currents, but which, nevertheless, profoundly influence such currents as soon as they arise. Thus we have the modifying influence of the coast. An ocean current impinging on a coast must change its direction to conform with that of the coastline. Glancing at Figure 40, we see, for example, that the South Equatorial Current on striking the coast of South America has its direction changed, part flowing northwesterly and part southwesterly, conforming to the trend of the coastline.

The most widespread agency operating on ocean currents is the deflecting force of the earth's rotation. This is an all-pervading force affecting every movement on the earth's surface. This force arises from the earth's rotation and tends to deflect a moving body to the right in the northern hemisphere and to the left in the southern hemisphere. Its strength varies directly with the velocity of the moving body and with the sine of the latitude, being zero at the equator and attaining its maximum value at the poles. As soon as a current is set up by any cause whatsoever, the deflecting force of the earth's rotation begins to operate. In the system of oceanic circulation, represented in Figure 40, we see its influence in the clockwise movement of the great eddies in the northern hemisphere and in the counter-clockwise movements in the southern.

From the preceding discussion it is clear that the movement of an ocean current is the resultant of the interplay of a number of agencies. Several of these agencies are of a variable nature, and hence we may expect variations of

one kind or another in the flow of an ocean current. In the main, however, there is a very large element of constancy in the system of oceanic circulation which may be represented as in Figure 40.

The rôle that ocean currents play in the economy of nature is an important one. Because of the very much greater velocities associated with the wind, it would appear at first glance as if ocean currents were but a minor factor in the transfer of heat from one locality to another. But it is not to be forgotten that, volume for volume, water has about three thousand times greater capacity for heat than air. And when the meteorologist attempts an estimate of the amount of heat carried from lower to higher latitudes, he finds that half is due to ocean currents and half to winds.

The climate of a given region depends not only on its latitude but also on the direction from which the winds blow. For clearly, if the winds come from colder areas they will lower the temperature of the given region, while if they come from warmer areas, they will raise the temperature. Winds blowing from the sea carry with them air whose temperature has been modified by the temperature of the sea water. Hence for a region in a given latitude the direction of the neighboring ocean current may be the decisive climatic factor. In the next chapter we shall consider in some detail the ameliorating influence of the Gulf Stream on the climate of northwestern Europe. Here we may note briefly an example of the opposite kind of effect.

Along the coast of southwest Africa, roughly between the 15th and 25th parallels of south latitude, an almost rainless district extends for a distance of about fifty miles inland. The temperature of the air here is very nearly ten degrees below what is normal for the latitude, but increases from the coast inland, despite the fact that the coastal highlands rise to more than six thousand feet above sea level. Furthermore, both winter and summer the in-

terior is warmer than the coast. It should be noted, too, that fog is an almost permanent feature along the coast.

The winds here are prevailingly from the south and southwest. Hence the relatively low temperatures obtaining may, perhaps, be ascribed to the winds which come from higher latitudes. But these winds sweep from the sea and are moisture-laden. Why should not, therefore, rain fall here in abundance? The anomalous climatic conditions find explanation in the effects of the neighboring ocean current. Glancing at Figure 40 we see that the Benguela Current flows past this coast. This is a cold current, bringing water from a higher latitude. The moisture of the air brought in with the winds from the sea becomes condensed to fog on striking the cold waters of the Benguela Current. On reaching the warmer land the air now becomes warmed, causing the moisture to become dissipated into clouds which drift inland.

Along the coast of South America the northerly-flowing Peru or Humboldt Current brings about climatic conditions quite similar to those obtaining in Southwest Africa. It must be added, however, that in both cases the cold water adjacent to the coast is not wholly due to the water brought by the current from higher latitudes. In part, too, it is due to the fact that these currents set somewhat westerly, that is, off the coast, and thus carry away the warmer surface waters which are replaced by upwelling of the colder subsurface waters.

Of all the currents which enter into the system of oceanic circulation, that known as the Gulf Stream is in many respects the most remarkable. It has been studied in much greater detail than any of the other great currents, so that its characteristics are better known. For these reasons, and also because of its far-reaching effects, the Gulf Stream merits more detailed consideration even in a general survey of the sea.

CHAPTER XVIII

THE GULF STREAM

IN 1855, Matthew Fontaine Maury, an American naval officer, published his *Physical Geography of the Sea*, which is frequently referred to as the first textbook of modern oceanography. In that publication he devotes the first chapter to the Gulf Stream, introducing it in the following words:

> There is a river in the ocean. In the severest droughts it never fails, and in the mightiest floods it never overflows. Its banks and its bottom are of cold water, while its current is of warm. The Gulf of Mexico is its fountain, and its mouth is in the Arctic Seas. It is the Gulf Stream. There is in the world no other such majestic flow of waters. Its current is more rapid than the Mississippi or the Amazon.

Even in matters scientific, customs change; for it is unlikely that an oceanographer nowadays would speak of the Gulf Stream as rhetorically as did Maury. The magnitude of this great current, however, is such that even later students make use of superlatives in describing it. The most comprehensive work in the Gulf Stream was done between the years 1885 and 1889 by Lieutenant (later Rear-Admiral) J. E. Pillsbury, U. S. N., while attached to the Coast and Geodetic Survey, when he carried out extensive velocity and temperature observations. And when he came to write up the results of his observations and studies he described it as "the grandest and most mighty terrestrial phenomenon."

The discovery of the Gulf Stream, or, more accurately,

the first notice on record, came about two decades after the discovery of the new world. Early in March of 1513, Ponce de Leon set sail from Porto Rico with three ships on a voyage of exploration. Apparently the purpose of the expedition was to search for land to the north of the West Indies, but legend would have it that this search of Ponce de Leon's was for a "fountain of perpetual youth." Setting a northwesterly course, the expedition discovered Florida, a landing being made on the eastern coast somewhere in the vicinity of Cape Canaveral. Sailing southerly then, on April 22nd they encountered "a current such that, although they had a great wind, they could not proceed forward, but backward." Thus was the Gulf Stream first noted.

Apparently the Spaniards soon learned that this northerly flowing current was not merely a local current, but one of wide extent; for six years later, when Antonio de Alaminos set out for Spain from Vera Cruz, he sailed northward with the Gulf Stream for a number of days before turning east toward Europe. This same Alaminos was pilot of Ponce de Leon's expedition of 1513 when the Gulf Stream was first noted. It is, therefore, quite proper to credit the discovery of the Gulf Stream to Alaminos.

During the following centuries the mariner became acquainted with the Gulf Stream throughout its course, but much of this information was kept as a professional secret. And it was not until after the middle of the eighteenth century that the course of the current was depicted on a chart. The story of how this came about is not without interest, especially as it illustrates nicely the effect of the Gulf Stream on navigation.

About the year 1770 the colonial authorities in America complained to the London officials that the English packets which came to New York took about two weeks longer in crossing than did the Rhode Island merchant ships which

put in at Narragansett Bay ports. Benjamin Franklin, being in London at the time, was consulted about the matter. To quote his own words:

> . . . it appearing strange to me that there should be such a difference between two places, scarce a day's run asunder. . . . I could not but think the fact misunderstood or misrepresented. There happened then to be in London, a Nantucket sea-captain of my acquaintance, to whom I communicated the affair. He told me he believed the fact might be true; that the difference was owing to this, that the Rhode-Island captains were acquainted with the Gulf Stream, which those of the English packets were not. . . . When the winds are but light, he added, they are carried back by the current more than they are forwarded by the wind. . . . I then observed that it was a pity no notice was taken of this current upon the charts, and requested him to mark it out for me, which he readily complied with.

Franklin goes on to relate that he had the information engraved "on the old chart of the Atlantic, and copies were sent to the captains of the packets who slighted it however." With the Revolutionary War coming on soon, Franklin didn't press his chart on the English mariners, and it was not till 1786 that he brought it to notice again in a paper in the *Transactions of the American Philosophical Society*. In Figure 41 we have the Gulf Stream as it appears on Franklin's chart.

In the figure the direction of the current is shown by the direction of the arrow, while the velocity is given in minutes of latitude per hour, that is, in knots. In the lower right hand corner we have a characteristic touch of the times, the picture representing Benjamin Franklin himself holding converse with Neptune.

Franklin also made observations on the temperature of the sea water during a number of voyages, and noted with regard to the Gulf Stream, "I find that it is always warmer than the sea on each side of it." He thought, too, "that

the thermometer may be a useful instrument to the navigator since currents coming from the northern into southern seas will probably be found colder than the water of those seas as the currents from southern seas into northern are apt to be warmer."

Systematic observations in the Gulf Stream were begun in 1845 by the Coast Survey under the superintendency

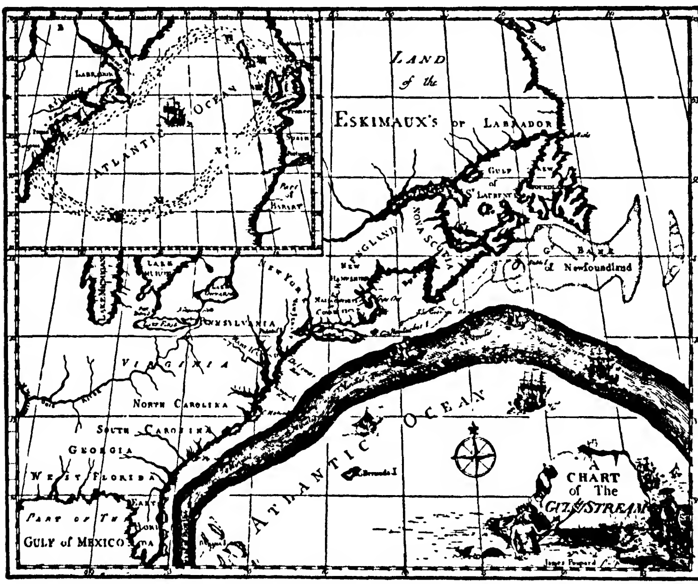

FIG. 41.—FRANKLIN'S CHART OF THE GULF STREAM

of Alexander Dallas Bache, a grandson of Franklin. At different times since then specially equipped vessels were detailed for the work. Under Pillsbury, as already mentioned, very comprehensive series of observations were obtained. While a great deal of research still remains to be done, especially in regard to variations to which the Gulf Stream is subject, the information at hand is sufficient for delineating the large features of this current.

Maury's picturesque phrase "a river in the ocean" has been shown by later researches as not applicable to

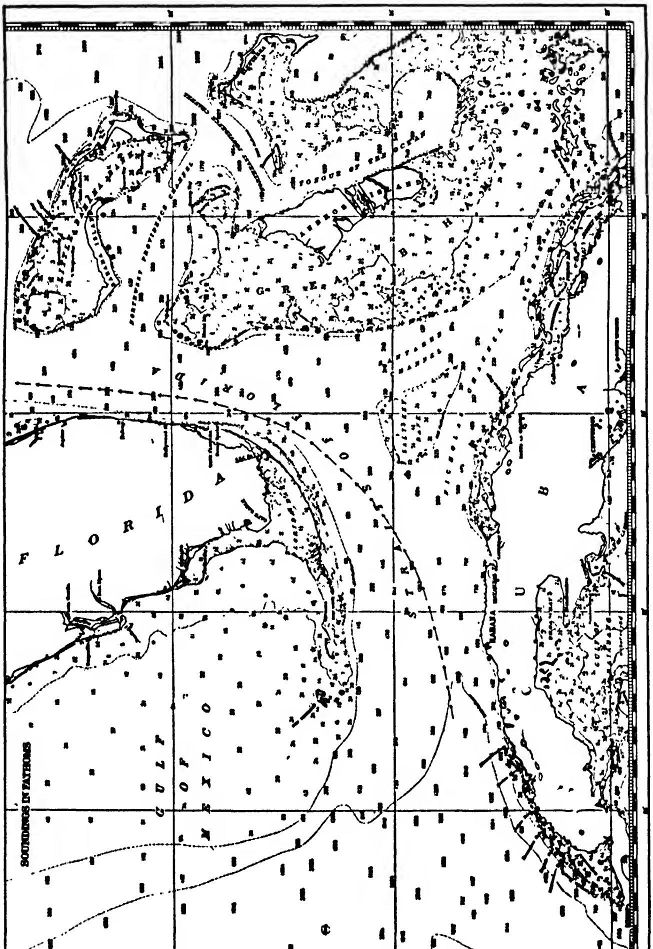

Fig. 42.—Hydrographic Features of the Gulf Stream Within the Straits of Florida

the Gulf Stream throughout the whole of its course. But for several hundred miles from its birthplace that description is very apt, as appears from an examination of the

hydrographic features of the region through which the Gulf Stream flows. Figure 42 shows these features for the first four hundred miles of its course. The arrows represent the axis of the Gulf Stream and the figures represent depths in fathoms.

Where the Gulf of Mexico narrows to form the channel between the Florida Keys and Cuba may be regarded as the head of the Gulf Stream. Here the width of its channel is 95 nautical miles. Eastward, toward the sea, the channel becomes narrower, reaching its least width in the so-called "Narrows" abreast of Cape Florida, where it is but half its original width. From here it widens somewhat until it meets the open sea north of Little Bahama Bank.

In respect to the changing width of its channel, the Gulf Stream differs from a river. For in the latter the channel as a rule increases in width from head to mouth. And in another respect, too, does the Gulf Stream differ from a river. In the latter the depths become greater from head to mouth. But the channel of the Gulf Stream becomes shallower from head to mouth as an examination of the soundings in Figure 42 shows. At its head we have depths of a thousand fathoms or more. From here the depths become gradually less, and where it meets the sea the greatest depth is but little over four hundred fathoms.

Throughout the whole stretch of four hundred miles shown in Figure 42 the Gulf Stream flows with considerable velocity. It is clear that this velocity will not be uniform, but will change as the cross section changes, becoming greater with a decrease in cross-sectional area and less with an increase in cross-sectional area. Furthermore, the velocity across any section is not uniform, being least close to shore and greatest in mid-channel or, more correctly, in the axis of the channel where it is deepest. The arrows in the figure trace the axis of the Gulf Stream.

Confining our attention for the present to the velocity at the surface, we find at its head, say abreast of Havana, the velocity in the axis of the Stream to be about $2\frac{1}{2}$ nautical miles per hour or $2\frac{1}{2}$ knots. Seaward, the velocity increases gradually as the cross-sectional area of the channel decreases, until abreast of Cape Florida the velocity becomes about $3\frac{1}{2}$ knots.

With regard to the current within the depths of the Gulf Stream, we have only fragmentary knowledge. In general, we know that the swiftest thread of the current lies in the axis of the stream just below the surface, and from here the velocity decreases with increasing depth. In the axis of the Gulf Stream at its head, the current was found setting easterly with a velocity of about one knot at a depth of 130 fathoms. This makes it probable that the current here is setting easterly to a depth of perhaps 500 fathoms. In the narrows off Cape Florida a velocity of $2\frac{1}{4}$ knots was observed at a depth of 130 fathoms. From other considerations it appears probable that here the current sets seaward all the way from the surface to very near the bottom.

If there were sufficient current observations, so that an accurate value of the average velocity of the current across any section might be computed, we would have the data that would permit the calculation of the amount of water the Gulf Stream pours into the sea. The observations at hand now permit only an approximation to this.

In round numbers the channel between Cape Florida and the Bimini Islands has a width of 42 nautical miles and an average depth of 2,000 feet or approximately one-third of a nautical mile. This gives the area of the cross-section here as 14 square miles. The surface velocity across this section averages about two knots. In round numbers we may, therefore, take the average velocity of the current across this section to be one knot. Each hour,

therefore, the Gulf Stream carries 14 cubic nautical miles of water past this section into the sea. Since a nautical mile has a length of 6,080 feet and a cubic foot of sea water weighs approximately 64 pounds, we find a cubic nautical mile of sea water to weigh approximately 7.2 billion tons. Each hour, therefore, the Gulf Stream carries 100 billion tons of water past Cape Florida into the sea.

The above calculation clearly is no more than an estimate; but it proves, nevertheless, that it is in scores of billions of tons that the hourly volume of the Gulf Stream is to be reckoned. Pillsbury, using somewhat different methods, arrived at a figure of 90 billion tons as the hourly volume past Cape Florida. More recently, the German oceanographer, Georg Wüst, in an hydrodynamic study of the Gulf Stream, arrived at a figure of 14 cubic nautical miles per hour. The data made use of by Wüst are not round numbers, but result from a careful study of all the factors involved. We may, therefore, regard 100 billion tons as an approximately correct figure for the hourly volume of the Gulf Stream past Cape Florida.

We may, perhaps, appreciate better the enormous volume of water that the Gulf Stream pours hourly into the sea by comparing it with the volume discharged by the mighty Mississippi River, which drains more than 40 per cent of the area of continental United States. On the average, the Mississippi discharges about 660,000 cubic feet of water into the Gulf of Mexico each second. At extreme flood stage, when its waters are carrying death and devastation in their wake, this volume becomes multiplied about threefold, mounting to about 1,800,000 cubic feet per second. On converting these figures into cubic (nautical) miles per hour, they become respectively 0.01 and 0.03 cubic mile. The 14 cubic miles which the Gulf Stream hourly pours into the sea is thus more than 1,000 times the average dis-

charge and nearly 500 times the extreme flood discharge of the Mississippi.

Coming now to a consideration of the characteristics of the water which the Gulf Stream pours so prodigally into the sea, we find it sharply distinguished in a number of respects from the sea water that is normal for its latitude. Referring back to Figure 13 (p. 137) we see that in latitude 27° N. the surface waters of the sea have an average salinity of just under 36. The surface waters of the Gulf Stream, where it empties into the open sea, have a salinity of a little more than 36. In the open sea, too, we find that in the lower latitudes, as a rule, the salinity decreases somewhat below the surface. In the Gulf Stream the case is reversed, the salinity being greatest at a depth of about 100 fathoms where it attains a value of about 36½. Below this depth the salinity decreases gradually, attaining near the bottom a value of about 35. As a whole, therefore, the waters of the Gulf Stream are characterized by a relatively high salinity.

With regard to temperature, the surface waters of the Gulf Stream stand out even more strikingly than in regard to salinity. Throughout the entire stretch of four hundred miles we have been considering, the average temperature of its surface waters is approximately 80 degrees. On referring to Figure 14 (p. 143) which gives the average temperature of the surface waters of the sea in the different latitudes, we find in latitude 27° N. the temperature is about 73 degrees. The surface waters of the Gulf Stream as they come out into the sea, therefore, have a relatively high temperature.

Below the surface the temperature of the Gulf Stream decreases at a rapid rate, quite in accordance with that found for the sea as a whole. Figure 43 represents in diagrammatic form the temperature within the depths of the Gulf Stream in the section across the narrows from Cape

Florida. The lines of equal temperature are drawn for each five degrees. The depths are measured in fathoms in accordance with the scale to the left, while the scale of nautical miles at the top gives the distance across the section from Cape Florida.

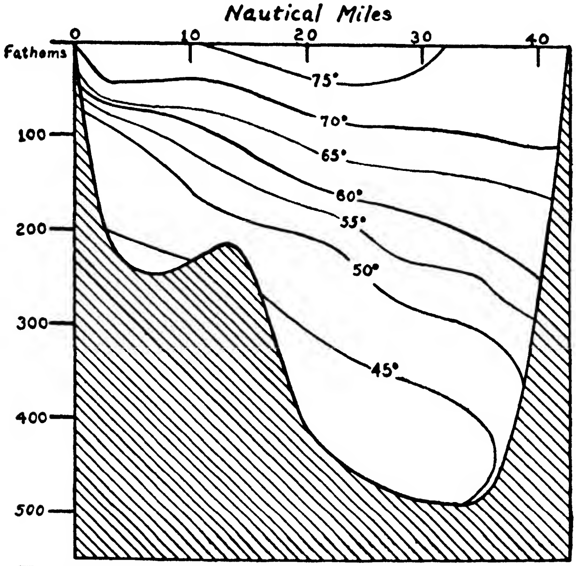

FIG. 43.—TEMPERATURE OF GULF STREAM WATERS WITHIN THE STRAITS OF FLORIDA

Several interesting features regarding the distribution of temperature within the Gulf Stream are brought out by Figure 43. The axis of the Gulf Stream may be taken as coinciding with the center of the channel in the section represented by Figure 43. Within this axis, from a surface temperature of about 80 degrees, the subsurface temperatures decrease at a fairly rapid rate. At a depth of 100 fathoms the temperature is about 70 degrees; at a depth of 200 fathoms, 55 degrees; and at 400 fathoms, 45

degrees. It is only in the upper layers, therefore, that the waters of the Gulf Stream are warm.

Figure 43 also brings out that for any given depth the water on the eastern side of the channel is considerably warmer than that on the western. Thus at the 100-fathom depth the water on the Florida side of the channel has a temperature of about 50 degrees, while on the Bahama Bank side of the channel the temperature is 70 degrees, or 20 degrees warmer. This difference in the horizontal distribution of the temperature is evidenced by the slope of the temperature lines.

The water of the Gulf Stream throughout the stretch under discussion is of the clear indigo-blue color characteristic of the waters of the tropical and subtropical regions. This whole stretch of the Gulf Stream may, therefore, be characterized as a swift, warm, highly saline current of blue water of great transparency. But we must be careful not to fall into the popular error of overrating the water of the Gulf Stream. Highly saline this water unquestionably is, but not exceptionally so, for in the Sargasso Sea in the same latitude we find the water more saline than in the Gulf Stream. With regard to temperature, too, the water of the Sargasso Sea, especially within the depths, is warmer. And, finally as regards color and transparency, the water in the Sargasso Sea is of a deeper blue and more transparent.

At its outfall into the sea north of Little Bahama Bank, the Gulf Stream flows due north, and it maintains that direction for a distance of about one hundred and fifty miles. The trend of the coastline in this stretch is northwesterly, and, as a result, the Gulf Stream appears to leave the coast. At its outfall, the axis of the Stream lies about thirty nautical miles from the coast, while off St. Augustine, Florida, about one hundred and fifty miles north, the distance has increased to eighty-five miles.

From the southern border of Georgia the coast begins trending eastward; and from the entrance to the Savannah River it runs in a general northeasterly direction for some three hundred miles until Cape Hatteras is reached. This change in the direction of the shoreline is reflected in the submarine topography, and from this cause alone we may expect a deflection toward the east in the Gulf Stream. To the effect of topography there is added, further, the effect of the deflecting force of the earth's rotation, so that off the coast of Georgia the axis of the Gulf Stream bears northeast, and this general direction it maintains past Cape Hatteras. The relation of the axis to the coast is shown in Figure 44.

Now it must be emphasized that the axis of the Gulf Stream as drawn in Figure 44 is a schematic representation only. The observations to date are not sufficient to locate the axis with any great precision. Furthermore, as we shall see later, the Gulf Stream is subject to variations, and only from long series of observations could the mean position of the axis be plotted with any pretense to precision. There is no question, therefore, that further research will make it necessary to change details here and there. Nevertheless, there is every reason to believe that the position of the axis of the Gulf Stream as shown in Figure 44 is approximately correct, at least in regard to its larger features.

On coming into the open sea the Gulf Stream loses much of its velocity. From 3½ knots at the outfall, the velocity along the axis decreases to about one and one-half knots off the coast of Georgia and to about one knot off Cape Hatteras. In the wider expanse of the open sea, too, the Gulf Stream does not possess the well-defined boundaries that characterized it through the Straits of Florida. The clearly defined limits, within which the Stream is represented as flowing in the open sea on the older charts, make a very

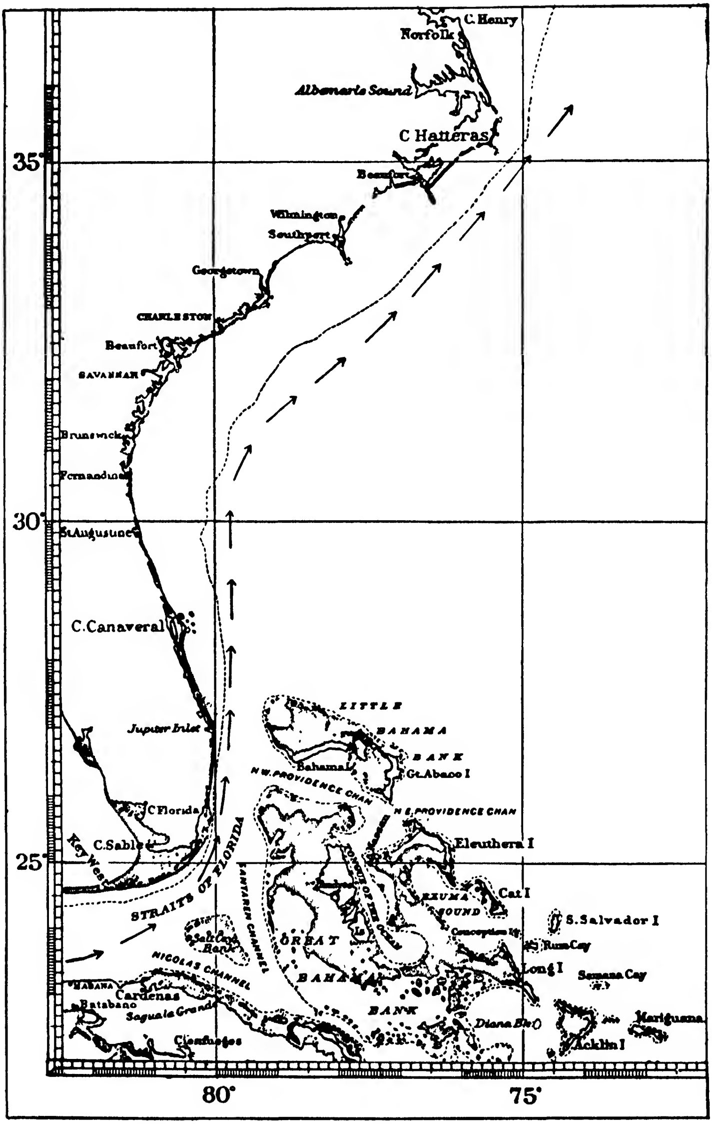

Fig. 44.—Axis of the Gulf Stream

pleasing picture. But, unfortunately, later research proved this picture to be altogether too simple to fit the facts.

In general, it may be taken that the western or inner limit of the Gulf Stream, from its outfall to Cape Hatteras, is defined by the 50-fathom curve. This follows the sweep of the coast but with not so bold a curve, so that at the ends of the arc it is from 10 to 20 miles offshore while in the center it is about 60 miles offshore. As a rule, the dividing line between the greenish coastal waters and the blue waters of the Gulf Stream is clearly marked.

To define the eastern edge of the Gulf Stream is extremely difficult, because from that side the Antilles Current comes to reënforce the Gulf Stream. From the map of ocean currents on page 252 we see that when the North Equatorial Current strikes the islands of the West Indies, one branch enters the Caribbean Sea while another branch skirts the islands, flowing northwesterly until it unites with the Gulf Stream in about latitude 30° N. This northwesterly branch of the North Equatorial Current is known as the Antilles Current. The Gulf Stream north of the thirtieth parallel of latitude, therefore, is a current to which two branches have contributed. It is no longer merely a continuation of the current which flows through the Straits of Florida. This latter current, for distinction, is frequently called the Florida Current.

Our knowledge of the Antilles Current is not sufficient for an exact determination of its extent and characteristics. It is known, however, to be a current of wide extent. And while not possessing such relatively great velocities as the Florida Current, it was considered until very recently the larger branch of the Gulf Stream. In regard to the quantity of water as well as the quantity of heat transported northward by the Gulf Stream, it had been accepted that the greater portion was contributed by the Antilles Current. Krümmel, for instance, in the second volume of his

standard treatise on oceanography, which appeared in 1911, credits the Antilles Current with contributing about two and one-half times as much water and heat as the Florida Current.

In 1924 Dr. Georg Wüst published his hydrodynamic study of the Gulf Stream. In this he considers critically all the observations made in the two branches of the Gulf Stream, subjecting them to the specialized mathematical analysis known as the method of dynamic sections which was developed in recent years by the Norwegian scientist, V. Bjerknes. From this study of Wüst's it appears that instead of the Antilles Current being the larger contributor, it is the lesser. He finds the Florida Current to contribute about twice as much water and heat to the Gulf Stream as the Antilles Current.

It should be noted that the Antilles Current, like the Florida Current, carries warm, highly saline water of clear indigo color. Where the two branches unite, in about latitude 30° N. we have, therefore, a broad current characterized by warm, blue water of relatively high salinity. In velocity, however, it no longer compares with that of the branch flowing through the Straits of Florida. It is no longer confined to a constricted channel, and in its journey of two hundred miles and more from the Straits, it has lost a considerable part of the impulse which sent it hurtling through its narrow channel.

On its inner edge the Gulf Stream is separated from the coastal waters by a zone of rapidly falling temperature. To this zone the appellation of "cold wall" is applied. It is most clearly marked north of Cape Hatteras, but extends more or less well defined from the Straits to the Banks of Newfoundland. The abrupt change in the temperature of the waters which the cold wall separates is frequently very striking. In 1922 the Coast Guard Cutter *Tampa,* while on Ice Patrol duty, was placed directly

across the cold wall and the temperature of the sea at the bow was found to be 34 degrees while at the stern it was 56 degrees. Since the *Tampa* is about 240 feet long, this means that within a distance of about 200 feet in the open sea there was a difference of 22 degrees in the temperature of the water.

Several agencies appear to be responsible for the cooler coastal waters along the eastern coast of the United States. In the first place it is into this area that the rivers bring their drainage waters from the land, these waters being for the greater part of the year much colder than the open ocean waters. Another contributory cause is the discharge of cold water from the Gulf of St. Lawrence, which the deflecting force of the earth's rotation forces against the American coast. The coastal waters, too, are closer to the low winter temperatures of the land and are thus cooled below the temperature of the open ocean waters. A further cause is found in the winds which along the coast of the United States are prevailingly from the land. This tends to drive the warmer surface water seaward, the place of this surface water being taken by the cooler subsurface waters.

After leaving its restricted channel in the Straits of Florida, the Gulf Stream tends to separate into bands of varying temperature. As a result, bands of warm water may be separated by a band of colder water. This feature becomes more marked as the Gulf Stream begins more and more to lose its identity northward of Cape Hatteras.

The region off Cape Hatteras has been called the "delta" of the Gulf Stream, for here the current splits into several branches. The branch flowing northeasterly is the largest and retains the name of Gulf Stream. With a velocity averaging a little less than a knot it continues its flow, turning more and more eastward in response to the deflecting force of the earth's rotation until the region of the

Grand Bank of Newfoundland is reached. Here it comes into conflict with the Labrador Current, which carries cold water of relatively low salinity.

The Gulf Stream proper may be said to have lost its identity after its encounter with the Labrador Current. The impulse which started it on its long journey of 1,800 miles from the Straits of Florida is now largely spent. The high temperature, high salinity and relatively great velocity that had characterized it farther southwestward, have gradually become less, and it has lost its deep blue color. The water the Gulf Stream has carried this far. however, still continues drifting easterly and northeasterly, but now it owes its movement primarily to the prevailing southwesterly winds. From here the oceanographer prefers to call the current the "North Atlantic Drift." As a slow current with a velocity of half a knot or less this moves northeasterly until it strikes the coastal waters of northwestern Europe, reaching as far as the northern coast of Norway.

The circulation of the surface waters in the North Atlantic Ocean, as it is portrayed on a modern current chart, is illustrated by Figure 45, which is adapted from Schott's *Geographie des Atlantischen Ozeans*. Three characteristics of the current are here indicated. The direction of the current at any point is shown by the direction of the arrow at that point; the strength of the current or its velocity is indicated by the width of the arrow; and the stability of the current is indicated by the length of the arrow. The stability of the current at any point is expressed as a percentage and is a measure of the constancy of direction of the current at that point. If it sets constantly in a given direction the stability is 100 per cent, and the lower the percentage, the more variable is its direction.

The movement of the waters from the warm regions of

the western Atlantic to the cooler regions of the eastern Atlantic, which is included under the general name of the Gulf Stream, stands out clearly also in charts that show the temperature distribution in the North Atlantic Ocean. Turning back to Figure 15, the northerly sweep of the temperature lines in the eastern North Atlantic brings out

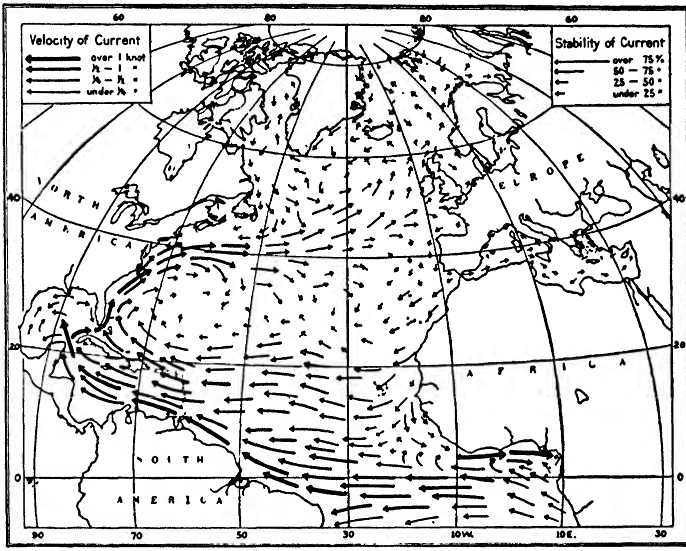

FIG. 45.—SURFACE CURRENTS, NORTH ATLANTIC OCEAN (AFTER SCHOTT)

at once the existence of a current moving northeasterly across this ocean basin.

It is clear that the Gulf Stream must be subject to fluctuations as regards temperature, velocity, and location. Heavy winds will not only accelerate or retard its velocity, depending on the direction of these winds, but will also carry its waters into regions which at other times it does not invade. Variations in barometric pressure likewise will bring about fluctuations in the movement of the Gulf

Stream. Furthermore, fluctuations in the currents which feed the Gulf Stream or which, like the Labrador Current, come into conflict with it will be reflected in the Gulf Stream. In view of the enormous volume of the Gulf Stream and of the many agencies concerned in its flow, it is obvious that such fluctuations in the Gulf Stream are of a relatively slight and temporary character.

The causes that bring about the Gulf Stream were considered briefly in the preceding chapter in connection with the causes of ocean currents in general. The trade winds bring about a westerly flow of the waters in the equatorial regions of the Atlantic Ocean. The waters of the South Equatorial Current are the first to strike the coast and the greater part is directed northwestward into the Caribbean Sea where it reënforces the flow of the North Equatorial Current. From the Caribbean the combined flow comes into the Gulf of Mexico, from which it issues as the Gulf Stream into the Straits of Florida. A little north of its outfall from the Straits of Florida the Gulf Stream is joined by the Antilles Current, which has branched from the North Equatorial Current and then skirted the islands of the West Indies.

That the warm waters of the Gulf Stream have an ameliorating effect on the lands in the vicinity of which they flow is a strongly held opinion. In our own country a prolonged cold spell or a period of unusual warm weather is sure to bring out statements that it was due to a shift in the course of the Gulf Stream. And schemes are seriously proposed now and again to change the course of the Gulf Stream with a view to moderating the winter climate of our northeastern states.

Now, as a matter of fact, the direct influence of the Gulf Stream on the climate of the greater part of the United States is altogether negligible. Even on places so close to the eastern coast as Norfolk, Washington, Balti-

more, and New York, its effect is insensible. For, aside from latitude, our climate depends mostly on the direction from which the winds come and the force with which they blow. But in winter the winds along the northeastern coast of the United States are prevailingly from the northwest, that is, from the land. Hence, unless the winter winds can be made to blow southeasterly in winter, bringing the Gulf Stream nearer our shores, they can in no way ameliorate the winter climate.

Indeed, the meteorologist is of the opinion that if the Gulf Stream were shifted nearer the coast the climate of our northeastern states would become more extreme, rather than moderated—colder and more stormy in winter, hotter and more humid in summer. For with warmer air near the coast in winter a greater flow of air from the northwest would result, bringing severer storms and colder weather. In summer, the winds along the coast are more or less sea breezes, bringing the cooler air from the sea to moderate the heat. With warmer air nearer shore, the sea breezes would become weaker and less frequent, thus giving greater range and wider scope for the hot land winds.

Nor can we assume so blithely our ability to shift the course of the Gulf Stream. Ocean currents, as we have seen, are governed by forces so great that they are not yet amenable to control by man. Grandiose though the schemes for changing the course of the Gulf Stream be, none has yet been proposed that is at all adequate to bring about the desired result. A shift in the course of an ocean current of the magnitude of the Gulf Stream can come only as the result of extensive changes in such features as the bottom of the ocean, the configuration of the coastline, or the prevailing direction of the winds.

And in this connection we may here consider the question of whether there has been any change in the course

of the Gulf Stream since it has been known to civilized man. Temporary and fleeting changes as a result of unusual conditions of wind and weather, we are compelled to admit. But since no extensive changes in the bottom of the ocean, the configuration of the coastline, or in the prevailing direction of the winds are known to have occurred within the past few centuries, it is highly improbable that any permanent change in the course of the Gulf Stream has occurred during that time.

While the effect of the Gulf Stream on the climate of North America is negligible, there is no question as to its beneficent effects on the climate of northwestern Europe. Scandinavia and southeastern Greenland face each other across the intervening waters of the Atlantic Ocean along the same parallels of latitude. Contrast the populous and prosperous lands of the one with the bleak and inhospitable shores of the other! As the Swedish meteorologist, J. W. Sandström, puts it, "Were it not for the ameliorating influence of the Gulf Stream, Scandinavia, like Greenland, would be covered with ice because of its northerly location and because of its closeness to the sea which favors heavy precipitation; and civilization, agriculture and forestry, which now flourish here, would be impossible. We may, therefore, here in Sweden truthfully say that we owe our existence to the Gulf Stream."

Now it must be carefully noted that the moderating influence of the Gulf Stream on the climate of northwestern Europe is effected through the agency of the winds. In winter the winds are here prevailingly from the southwest. Blowing over the warm water which the Gulf Stream has brought to the northeastern rim of the Atlantic, the air carried on to the coast is warm air. It is through this mechanism that the heat exchange in winter between the Gulf Stream and the air of northwestern Europe takes place.

The influence of the Gulf Stream through the agency of the southwesterly winds becomes evident from the fact that the average temperature for the month of January is in northern Norway about 45 degrees above the January temperature normal for that latitude. Hammerfest, on the north coast of Norway, in latitude 70° 40′ N.—well within the Arctic circle—is an important harbor and fishing center during the winter, while the port of Riga about 800 miles farther south is obstructed by ice throughout the winter.

Since the climate of northern Europe is so strongly influenced by the Gulf Stream, should not fluctuations in the latter find reflection in changes in the climatic conditions of this region? Furthermore, since it is a long circuit that the waters of the Gulf Stream must traverse from the place of origin in the subtropical regions to the northern coasts of Europe—one that takes many months to complete—should it not be possible from observations in the Gulf Stream to forecast variations in climatic conditions months ahead? Both questions have of late years received attention.

From observations made in the waters of the Gulf Stream, it is found that the temperature varies somewhat from year to year. These variations are small, the average temperature from one year to another differing by about one degree. And while the variation of a degree or two in the annual temperature of the Gulf Stream may appear insignificant, the effect of this variation on the temperature of the colder regions toward which the Gulf Stream bears its freight of warm water may be of importance, for it is to be kept in mind that when a given volume of water gives off the heat represented by a drop of one degree in temperature, a mass of air more than 3,000 times that volume will have its temperature raised one degree.

The Scandinavian oceanographers in particular have been interested in the problem of the relation of variations

in the Gulf Stream to changes in climatic conditions. This matter is not only of scientific interest but is also of great practical importance. Otto Pettersson found from records extending over a number of years that the date at which spring plowing could be commenced near Upsala in Sweden depended on the temperature of the water of the Atlantic off the coast of Norway two or three months previous. Vilhelm Pettersson has shown a very striking relationship between the summer temperature of the water in the region east of Newfoundland and the rainfall in Ireland and Great Britain in the following year.

Obviously, the problem of unraveling the relationship between changes in the Gulf Stream and weather conditions several months hence is not a simple one. Climatic conditions in any given region of the North Atlantic result from the interplay of a number of factors. Similarly, the temperature of the Gulf Stream at any given time is brought about by the interaction of a number of agencies. Nevertheless, it appears that in a study of the fluctuations of the Gulf Stream lies the possibility of long-range weather forecasts for a considerable part of Europe.

CHAPTER XIX

THE SCIENCE OF THE SEA

THE great body of organized knowledge which mankind has accumulated under the name of science is divided among a number of different sciences. This division, however, is only for convenience in study and research, for the unity of science is one of its characteristic features. Each so-called science is, in reality, but a branch of Science, for any one field of scientific investigation ties in so very intimately with every other field that only by arbitrary limits can they be separated. It would not be difficult to prove, for example, that to thoroughly explore any one aspect of nature requires the development and use of our full store of scientific knowledge.

These considerations apply with special force to the sea. So many and so far-reaching are its relations with the rest of nature that to develop a science of the sea in all its possible ramifications would be productive of a science embracing not only the sea but all animate and inanimate nature. Such an all-inclusive science would be extremely inconvenient for study and research. As actually developed, therefore, under the name of oceanography, the science of the sea embraces primarily the study of the form and nature of the oceanic basins, the characteristics of the waters in these basins, and the movements to which these waters are subject. Even as so restricted, the problems that confront the student of oceanography are not only of wide scope but also extremely varied in character.

When a branch of knowledge is designated as a science,

it is implied that the subject matter has become integrated into a closely knit body of knowledge, that the multitude of facts dealt with have become interrelated through principles and hypotheses of wide application, and that quantitative relationships between many of the phenomena have been formulated. The ancients, as we have seen, had knowledge of the sea; but this was merely part of the general fund of information and consisted largely of isolated items of information, useful or interesting. Pliny, to be sure, thought rather highly of the state of knowledge regarding the sea in his time. In his *Historia Naturalis,* after cataloguing the number of marine animals known, he exclaims, "By Hercules, in the sea and in the ocean, vast as it is, there exists nothing that is unknown to us; and, a truly marvelous fact, it is with those things that nature has concealed in the deep that we are best acquainted!"

In the development of a science three stages can usually be recognized. There is, first, the stage that is concerned with gathering the facts bearing on the subject; this is followed by the stage in which the accumulated information is classified and systematized; and, in the last stage, the various groups of facts are interpreted and related to each other through generalizations or so-called laws. This does not mean that sharp dividing lines separate one stage from another, for customarily interpretations are made and generalizations attempted on very meager bases of fact. But it is only after a sufficient body of facts has been accumulated, this body classified and systematized, and the various groups of facts interpreted and interrelated, that we speak of that field of knowledge as a science.

It is clear that a science of the sea could come into being only at a relatively late date. For the very first stage—the gathering of a sufficient body of pertinent facts—necessitated not only a great deal of time-consuming and costly labor because of the vast field to be covered, but was de-

pendent also on the prior development of other sciences and of various arts. Before the extent of the sea could be ascertained, it was necessary that shipbuilding and navigation should reach high development; the successful sounding of the depths of the sea could come only after the development of numerous technical arts; not until physical and chemical methods had been perfected could the characteristics of the water of the sea be accurately determined. Indeed, as we have found, many of the basic facts have become known only in recent years.

Even after a sufficient body of information was acquired, the task of systematizing the material—the second stage of scientific development—was in oceanography more difficult than in many other sciences. In the first place, the field with which oceanography deals is so vast that a given phenomenon may manifest itself quite differently at different places. For example, the distribution of temperature within the depths of the sea is altogether different in the polar regions than in the tropics; the rise and fall of the tide varies in striking manner in different regions; an ocean current at one place may be very nearly constant, while at another place it may be subject to bewildering variations.

In the light of these considerations, it is clear why the third stage of scientific development, the integrating of the various groups of facts through general principles and hypotheses, came at a late date. In the family of sciences, oceanography is one of the younger members, not having yet attained the dignity of a centenary. To be sure, certain branches of the subject attained high scientific development considerably more than a century ago. Tidal theory, for example, bears the impress of the labors of Newton in the seventeenth century and of Laplace in the eighteenth century. But these great scientists were interested in the matter, not as a problem of the sea, but as a problem in astronomy and celestial mechanics.

It is of interest, too, in this connection, to note that in the *Geography* of Bernhard Varenius, which appeared in 1650, the part dealing with the sea is most infused with the scientific spirit. It is customary, however, to date the emergence of oceanography as a distinct branch of science with the publication in 1855 of Maury's *Physical Geography of the Sea,* which, as noted in a previous chapter, is frequently referred to as the first textbook on modern oceanography. Under the phrase "physical geography of the sea" Maury comprehended what is now called "oceanography," the latter term not having yet been coined.

As an officer in the United States Navy, Maury had spent a number of years at sea, circumnavigating the globe during one cruise. Later, while in charge of the Depot of Charts and Instruments, out of which the present Hydrographic Office and the Naval Observatory have grown, he began the compilation and study of winds and currents in the interests of navigation. His *Wind and Current Charts* were of direct practical utility to the mariner, who, by their use, shortened his voyages by a number of days. It was as a result of Maury's labors, too, that an international congress was held at Brussels in 1853 in the interest of uniform oceanographic observations on the part of mariners.

While thus engaged primarily in practical problems affecting navigation, Maury realized the importance of a scientific study of the sea. The *Physical Geography of the Sea* was the result. Written in what might now be regarded as a somewhat rhetorical manner, we here find the sea viewed as the subject matter of a distinct branch of knowledge with problems all its own. The importance of these problems, and their inherent interest, Maury discusses with the enthusiasm of a man dealing with a subject he knows well and loves well.

Here it may be noted that the motives that have underlain ocean studies have, to the present time, been very largely of a practical nature. The first crossings of the oceans and the earlier searches for the Northeast and Northwest passages were wholly in pursuance of practical aims of an immediate nature. Maury's studies received governmental support and the coöperation of the practical mariner because of their utility in shortening the duration of ocean voyages. In connection with his practical work of laying transoceanic telegraph cables, the cable engineer encouraged the sounding of the depths of the oceans. And in connection with practical fishery problems the marine biologist is compelled to study the physical and chemical characteristics of the ocean waters.

A complete list of the practical problems, work on which furnished important data for the science of oceanography, would require many pages. Those cited above are merely by way of illustration. The result of this state of affairs was that for many years the sea was regarded as a field for the exercise of a large number of specialized sciences rather than as furnishing the subject matter of a distinct branch of science. With Maury comes the recognition of the unity of this branch of science, and with the *Challenger* Expedition some twenty years later comes the formal framework as well as the name of oceanography.

The *Challenger* was a war vessel which the British Government was prevailed upon by the Royal Society to send out on a strictly scientific study of the sea. Under the leadership of Professor C. Wyville Thomson, the expedition sailed from England in December of 1872, and spent nearly three and one half years on the sea, circumnavigating the globe and traversing the oceans in various directions. The scientific results, published in fifty large volumes, which appeared between the years 1880 and 1895, make this the most notable oceanographic voyage. It is

of interest to note, however, that of this published material much the greater part deals with marine biology.

The results derived by the *Challenger* Expedition, and more particularly the coördination and interpretation of the existing data, laid the firm foundations for the science of the sea. Oceanography as the name for this science came as a result of this expedition, for it appears to have been introduced by Sir John Murray about 1880. Murray was a member of the scientific staff of the *Challenger*, and it was mainly under his direction that the results of the expedition were published.

Following upon the *Challenger* Expedition came oceanic expeditions sponsored by various governments or scientific organizations. The cost of an oceanic expedition is clearly very considerable, so that it is, as a rule, wholly beyond the means of the average scientist. Occasionally, some wealthy individual with scientific tastes is attracted to this field with gratifying results. Thus, the late Prince Albert of Monaco had devoted considerable time and money to oceanic studies. It was under his auspices that a splendid series of charts of the depths of the sea, the "Carte Générale Bathymétrique des Océans" was issued, and his memory is fittingly perpetuated by the magnificent oceanographical museum which he built at Monaco.

While oceanography is now a well-established branch of science, certain features tend to limit the number of its students as compared with other sciences. In most sciences, observational data can be secured by the student wherever he may happen to be. The astronomer may set up his instruments and make his observations on the heavenly bodies at any desired point. The meteorologist, the geologist, the chemist, the physicist, and the student of most other sciences, may carry on his researches wherever domiciled. But not so the oceanographer. The subject matter of his science being the sea, he is compelled to derive his observational

data along the coast or out in the open sea. And since the greater number of people live out of sight and sound of the ocean, the study of the sea has not attracted the attention given to other sciences. In our own schools and universities, for example, it figures but rarely as a major subject of study.

There are signs, however, that we are entering a period in which the sea will be subject to more widespread and intensive study. Various technical problems arising in connection with commercial and industrial activities necessitate more thorough oceanographic knowledge. Thus, in connection with safeguarding navigation, the various governments are making very careful surveys of the coastal waters and studying their tides and currents. With the same object in view, fourteen maritime nations are sharing the costs of the International Ice Patrol of the North Atlantic which, in connection with its patrol duty, is engaged in carrying out a program of oceanographic investigations. In connection with datum planes and with problems involving property rights along the coast, a more detailed study of the level of the sea and of its variations is being made.

In numerous other practical fields the need for detailed knowledge regarding the sea is acting as a stimulus to further oceanographic research. A complete enumeration would result in a long list, which would be out of place here. The fisheries, however, must be mentioned. That a thorough knowledge of the sea must underlie the intelligent handling of the sea fisheries is axiomatic, and in connection with fishery problems a very considerable amount of oceanographic work has been carried out. In this field the International Council for the Study of the Sea has taken a leading part. Organized in 1901, with headquarters at Copenhagen, and consisting of members from the various countries facing the North Sea and sur-

rounding waters, it aims at the improvement of the fisheries in these waters. By encouraging and coördinating the oceanographic work of its member countries, this Council has acted as a powerful stimulus in forwarding the study of the sea.

Coincident with the growing recognition on the part of the practical world of the need for more detailed study of the sea, comes the increasingly insistent demand from the scientific world for further oceanographic research. As one student recently put it, "many branches of science meet in and upon the sea." Meteorology, geology, marine biology, geodesy, volcanology, and a number of other sciences are confronted by problems that involve a knowledge of the sea. Indeed, it may be said that no matter what aspect of nature we may attempt to understand, sooner or later we come across features that bear the impress of the sea.

This fundamental importance of oceanography in the family of sciences is gaining wide recognition in scientific circles and is bound to result in greater activity in oceanic research. As heralds of this era of greater oceanographic activity, the two recent expeditions on board the *Meteor* and the *Carnegie* may be cited. The *Meteor* is a converted man-of-war, which was fitted out with a full complement of modern oceanographic apparatus for an intensive study of the oceanography of the South Atlantic Ocean. Under the scientific leadership of Dr. Alfred Merz of the Oceanographic Institute of the University of Berlin, the *Meteor* left Germany in April, 1925, and spent over two years in the South Atlantic, returning to Germany in June, 1927. The preliminary reports which have appeared to date give evidence that the full scientific results of this expedition will constitute an outstanding contribution to the science of the sea.

The *Carnegie* is the well-known nonmagnetic ship which

he Department of Terrestrial Magnetism of the Carnegie nstitution of Washington has used in its magnetic surveys f the oceans. In May, 1928, it left Washington on its eventh cruise, which is to traverse more than a hundred housand miles and to extend over a period of three years. Vhile engaged primarily in magnetic and related work, ceanographic investigations have been included as a part f the program; and, under the scientific leadership of its ommander, Capt. J. P. Ault, oceanographic data of basic mportance may be looked for as a result of this cruise.

While oceanography is of help to various other sciences, t must, in turn, look to other sciences for help in the solu-ion of its own problems. In this respect, oceanography s one of the most synthetic of sciences. Thus, for the ccurate determination of the extent of the sea and of the orm of its surface, it must invoke the good offices of eodesy; the tidal movements of the sea are bewildering vithout the help of astronomy; a thorough understanding f the nature of the bottom of the sea is impossible without ecourse to geology and biology; and chemistry and physics bviously must be asked to help in studying the charac-eristics of sea water.

In a general survey of our knowledge of the sea, such s was attempted in the preceding chapters, it is clear that nly the more salient features can be considered. This may ead to the impression that oceanography is wholly a de-scriptive science, consisting of an accumulation of facts scertained by simple measurement or observation. Such n impression would be a misleading one, for oceanography as progressed beyond the stage represented by the mere massing of facts, important as that still is, to the stage n which problems are formulated that demand for their olution the application of mathematics.

There is an oft-quoted saying of the great philosopher Kant to the effect that the amount of real science to be

found in any subject is the amount of mathematics contained therein. Like all epigrams this is too sweeping in its statement; but there can be no question that as a science progresses, it makes increasing use of mathematics. Oceanography itself bears witness to this; for it has advanced most in those directions in which mathematics has been most used.

The tide furnishes an illuminating example. For many years merely an impressive manifestation of the mysterious power of sun and moon over the waters of the earth, the subject early attracted the attention of the mathematical astronomer because of its importance in connection with certain problems in astronomy and in celestial mechanics. As a consequence, the tide has received high mathematical development, leading not only to a more complete understanding of its diverse manifestations, but also to mechanical means for its prediction for as long a period in the future as may be desired.

In the development of the mathematical theory of the tide a number of interesting collateral problems have been brought to light. As examples may be mentioned the determination of the mass of the moon and of the rigidity of the earth from the observed heights and times of the tide, and the effects of tidal friction. This latter problem it will be of advantage to summarize briefly, not only because of its inherent interest but also as illustrating how far-reaching in its effects some seemingly inconsequential feature of the sea may be.

The tidal movements of the sea are obviously accompanied by friction, arising chiefly from the movement of the water over the beds of the oceans, seas and rivers. This friction consumes energy, and it can be shown that this consumption is at the expense of the earth's store of energy. In other words, tidal friction acts as a sort of brake on the rotating earth, tending to reduce its rota-

tional velocity and, as a consequence, tending to make the day longer. The stock of energy possessed by the earth is, however, so enormous as compared to the frictional loss due to tidal friction, that it is only by a very minute quantity that the day is lengthened by this cause—something like the thousandth part of a second in a century.

The effect of tidal friction is not confined to the earth alone, but makes itself felt also on the moon. A mathematical investigation proves that besides decreasing the rotational velocity of the earth, tidal friction also tends to increase the distance between earth and moon. This increase in distance, like the increase in the length of the day, is at an exceedingly slow rate. But it is to be kept in mind that tidal friction has been operating, literally, from time immemorial; so that the cumulative effects must by this time be considerable. If, therefore, we go backward in time it follows that the day must have been shorter and the moon nearer.

Now when the moon was nearer the earth, the tides must have been much larger than at the present time; for we found, in our consideration of the tide in Chapter XV, that the tide-producing power of a heavenly body varies inversely as the *cube* of its distance. And quite apart from the increased friction due to the greater tides, tidal friction also varies inversely as the *cube* of the moon's distance from the earth. The efficiency of tidal friction in increasing the length of the day and the distance between moon and earth therefore varies inversely as the *sixth* power of that distance. So that when the moon was half her present distance from the earth the effects of tidal friction were at a rate $2^6 = 64$ times as great as now.

Starting with these considerations, the English mathematical astronomer, Sir George Darwin, investigated the subject mathematically and developed an exceedingly interesting and very plausible theory as to the early history

of earth and moon, from which it appears probable that the moon was at one time part of our earth. Such a theory is, to be sure, based on speculation; but it is tempered scientific speculation which does not run counter to the known laws that govern the universe.

To return from this digression, ocean currents may be cited as another example of the fruitfulness of the application of mathematics in the study of oceanography. The direct measurement of the velocity and direction of the current in the open sea is a problem of such magnitude that it must be ruled out as a practicable method for the study of ocean currents The other means of a more or less direct nature which have been used for this purpose, such as drift-bottles and other floating objects, give but a partial and very limited picture of the circulation of the sea, for they show nothing of the movement of the water within the depths of the sea. In fact, the only satisfactory practical means for studying ocean currents, to date, is based on theoretical mathematical considerations. By taking account of the forces involved in bringing about currents, the Scandinavian oceanographers—Bjerknes, Ekman, Sandström, Helland-Hansen and their colleagues—have developed a mathematical method by means of which a knowledge of the temperature and salinity of the water at various depths at several stations permits the computation of the velocity and direction of the current at these depths

Even though our survey of the sea in the preceding pages was confined to a consideration of the larger features only, we nevertheless found that many basic facts still remain to be ascertained by direct observation. Extensive regions, covering thousands of square miles in area, have never yet been sounded. The bottom of the sea has been merely scratched in a few places; what may it not reveal of the past history of our earth when we come to know its nature to a depth of a number of feet? How much re

mains to be known of the exact composition of the sea water and of its variations, is illustrated by the fact that the gold content as recently determined by the *Meteor* Expedition was about one thousand times less than had been taken for granted previously. To what variations, precisely, are the different ocean currents subject? The list could be multiplied indefinitely.

With many basic facts still awaiting discovery, it is obvious that oceanography still offers the student plenty of opportunity for the correlation and systematization of its data. An even wider opportunity is afforded in the interpretation of the data and in integrating them into closely knit relationships. And for those possessing the necessary mathematical training there are many problems that tax resourcefulness and ingenuity to the utmost. Oceanography is clearly a fertile field for investigation.

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